

ARMY RESEARCH LABORATORY



Induction Heat Treatment - Phase I - Technology to Produce Monolithic Gradient Hardness Steel Armor

Richard J. Squillacioti

ARL-TR-1193

September 1996

DTIC QUALITY INSPECTED 4

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

19961008 014

NOTICES

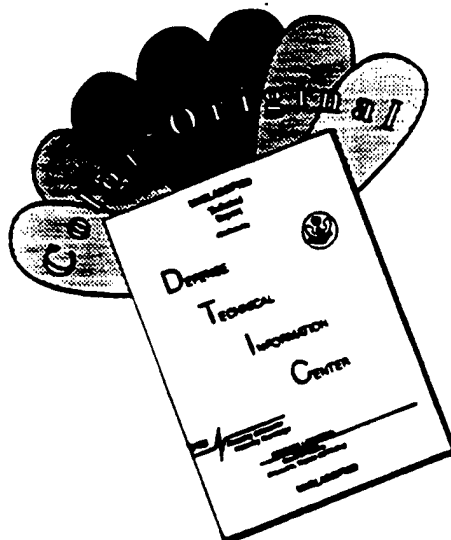
Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF COLOR PAGES WHICH DO NOT REPRODUCE LEGIBLY ON BLACK AND WHITE MICROFICHE.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

September 1996

3. REPORT TYPE AND DATES COVERED

Final, 1993 - 1995

4. TITLE AND SUBTITLE

Induction Heat Treatment - Phase I - Technology to Produce Monolithic Gradient Hardness Steel Armor

5. FUNDING NUMBERS

N/A

6. AUTHOR(S)

Richard J. Squillacioti

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-MA-PD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION
REPORT NUMBER

ARL-TR-1193

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Program Manager, Survivability
U.S. Army Tank-Automotive Command (TACOM)
Warren, MI 48397-5000

10. SPONSORING/MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report details the results of Phase I of the Dual Hard Steel Armor Program funded by the PM, Survivability, U.S. Army Tank-Automotive Command (TACOM). This report investigates the use of an induction heat-treating process to produce a gradient hardness monolithic steel armor to complement MIL-A-46099, Armor Plate, Steel, Rolled-Bonded, Dual-Hardness, for thicknesses of approximately 0.5 in.

Results of this investigation indicate that a conventionally heat-treated steel armor plate (tempered to a hardness range of Rc 42-52; induction-hardened to approximately Rc 60 and induction tempered to approximately Rc 50 with a high hardness thickness of approximately 40%) will provide acceptable ballistic results when compared to the ballistic requirements of MIL-A-46099. Future efforts (Phase II) will include optimization of the composition, hardness levels, and thickness gradients. Production-size plates will also be processed to ensure that the technology can be transitioned from the laboratory to production.

14. SUBJECT TERMS

induction heat treatment, dual hard steel armor, monolithic, gradient hardness

15. NUMBER OF PAGES

55

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION
OF THIS PAGE

UNCLASSIFIED

19. SECURITY CLASSIFICATION
OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENTS

The author acknowledges Mr. Raymond A. Cellitti of R. C. Associates (under Government contract) for his assistance and technical advice provided during the execution of this program. His dedication to the project is highly commendable.

The author also acknowledges Mr. George D. Pfaffmann of TOCCO, Inc., for his continuing effort to ensure the implementation of the Cooperative Research and Development Agreement between his company and the U.S. Army. Mr. Pfaffmann is also commended for developing a professional working relationship/environment within his company that will guarantee a successful completion of this project and others that will follow.

Finally, the author acknowledges the following U.S. Army Research Laboratory, Materials Directorate (ARL/MD) individuals for their contributions.

Joseph Prifti
Michael Castro
Joseph Lucas
Dennis Gosselin
Joseph Maddalena
Anthone Zarkades
Daniel Snoha

James Brown
Mark Taylor
Francis Hannahan
George Dewing
Karen Heavey
Dino Papetti

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	iii
LIST OF FIGURES	vii
LIST OF TABLES	ix
1. OBJECTIVE	1
2. BACKGROUND	1
3. INTRODUCTION	2
4. PROCEDURE	3
5. RESULTS/DISCUSSION	4
6. CONCLUSIONS	6
7. RECOMMENDATIONS	7
APPENDIX A: EQUIPMENT PHOTOGRAPHS	23
APPENDIX B: PHOTOGRAPHS OF JESSOP STEEL CONVENTIONAL ROLLED BONDED MATERIAL	29
APPENDIX C: PHOTOGRAPHS OF HEAT NO. 4353	33
APPENDIX D: PHOTOGRAPHS OF HEAT NO. Z-62A FIRST POUR	37
APPENDIX E: PHOTOGRAPHS OF HEAT NO. Z-62A FIRST POUR SECOND SERIES	47
DISTRIBUTION LIST	57

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Standard dual hard Jessop steel	13
2. Standard dual hard Jessop steel	14
3. Heat No. Z-62A first pour - plate No. 2B	15
4. Heat No. Z-62A first pour - plate Nos. 1A, 2A, and 3A	16
5. Heat No. Z-62A first pour - plate Nos. 1B, 2C, and 3B	17
6. Heat No. Z-62A first pour - plate Nos. 15, 18, 8, and 14	18
7. Heat No. Z-62A first pour - plate Nos. 20, 23, 17, and 19	19
8. Heat No. Z-62A first pour - plate Nos. 22, 5, 1, and 11	20
9. Heat No. Z-62A first pour - plate Nos. 13, 21, 6, and 7	21
A-1. Overall view of work station and controls with quench system and RF transformer ..	25
A-2. RF power supply and RF transformer	25
A-3. AF power supply that feeds into the AF transformer	26
A-4. AF transformer housing, station controls, and quench system	27

INTENTIONALLY LEFT BLANK.

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Ballistic Testing of Rolled Bonded Dual Hard Material	8
2. Chemistries of In-House Heats	8
3. Ballistic Testing of Monolithic Dual Hard Material Heat No. 4353	9
4. Ballistic Testing of Monolithic Dual Hard Material Heat No. Z-62A/1	9
5. Ballistic Testing of Monolithic Dual Hard Material Heat No. Z-62A/1	10
6. Hardness Profile vs. Ballistics (0.50-cal. AP M2)	11
7. Hardness Profile vs. Ballistics (0.50-cal. AP M2) at 30° Obliquity	12

INTENTIONALLY LEFT BLANK.

1. OBJECTIVE

The objective of the Induction Heat Treatment Program is to improve the current technology of processing metallic armor materials by using induction heat-treating equipment. Phase I of the program is to produce monolithic gradient hardness armor steel using the induction heat-treating process to complement MIL-A-46099¹ (i.e., prove the principle that induction hardening and tempering can produce a monolithic gradient hard steel armor plate that can satisfy the ballistic requirement of MIL-A-46099).

Future efforts to complete the Induction Heat Treatment Program will have the following objectives: (1) Phase II of the Program will attempt to determine optimum alloy composition and hardness profiles in the 5/16- to 1-in thickness range that provide the highest ballistic performance while maintaining the plate's integrity with respect to armor piercing (AP) threats. Phase II will also extend the technology to production-size plates. (2) Phase III of the Program will investigate the development of ductile skins on ultrahard armor materials. (3) Phase IV will extend the technology to other materials, such as titanium.

Under a Cooperative Research and Development Agreement (CRDA), TOCCO, Inc.,² will transfer the technology to industry. The potential of applicability in the civilian sector (commercial applications) is unlimited.

2. BACKGROUND

In 1989, the U.S. Army Research Laboratory/Materials Directorate (ARL/MD) (formerly Materials Technology Laboratory) purchased an Audio Frequency/Radio Frequency (AF/RF) Induction Unit from TOCCO, Inc., and modified in-house for selected use in developing improved armor steel plate. The research was aimed at developing procedures to obtain various hardness gradients within the steel armor monolithic structure. The equipment was installed (in Building 43), modified, and tested for proper operation during 1990. Research began shortly thereafter. However, with the announcement of the closure and the cleanup of the ARL/MD site (Watertown, MA), research stopped. Building 43 was one of the first buildings to be cleaned, so the Induction Unit was disconnected, crated, and stored in

¹ Department of Defense. Armor Plate, Steel, Rolled-Bonded, Dual-Hardness. Military Specification MIL-A-46099, Revision C, 14 September 1987.

² Cooperative Research and Development Agreement (CRDA), Induction Heat Treatment of Steel Armor, between the U.S. Army Research Laboratory/Materials Directorate (ARL/MD) and TOCCO, Inc., May 1993.

Building 37. The expense of reassemble and hookup to an operating status was determined not to be cost effective in light of the remaining time ARL/MD would be operational at the Watertown site. In an effort to use the equipment between 1993 and 1997 (relocation date/new facility completed at the APG, MD) and to keep the equipment in working condition, a Cooperative Research and Development Agreement was established between ARL/MD and TOCCO, Inc. The equipment was crated and shipped to TOCCO, Inc. (Madison Heights, MI), on 31 May 1993.

The operational setup of the equipment at TOCCO, Inc., encountered delays due to component breakage in shipping and handling. Modification of various components of the equipment was also required. The equipment became operational through the combined efforts of TOCCO, Inc. personnel and Mr. Raymond A. Cellitti, President, R. C. Associates, Hinsdale, IL. Photographs of the equipment (at TOCCO, Inc.) are shown in Appendix A.

During this timeframe, Jessop Steel (producer of rolled bonded dual hard armor steel) was contacted for samples of dual hard material. This material was ballistically tested at ARL/MD and analyzed for hardness profiles (thickness of the individual rolled bonded plates and the hardness levels of each). The results are discussed in future sections of this report.

Prior induction heat treat processing work was performed at the U.S. Naval Ordnance Laboratory in White Oaks, MD. Two reports were generated from this work, namely, "Studies on a Steel Gradient Hardened Armor," D. Goldstein and W. J. Buehler, 30 July 1969, Report No. NOLTR 69-129; and "Scaling-Up Studies on Steel Gradient Hardened Armor - Part 1," D. Goldstein, 31 July 1970, Report No. NOLTR 70-106. A classified patent was filed on 1 July 1971 by D. Goldstein, Case No. 50346. Due to the changes in the Security Classification Guide, declassification of this patent is in progress.

3. INTRODUCTION

This is the first report documenting the results from using induction heat treatment to produce improved gradient hardened armor steel. The focus of this research effort is to investigate the feasibility of various methods to produce monolithic gradient hardness armor steel to complement MIL-A-46099.

Induction heating is an extremely versatile method for hardening steel. Uniform or localized surface hardening, through-hardening, and tempering of hardened plates may all be performed by induction heating. The heating of a steel plate is accomplished by placing the plate within a magnetic field generated by a high-frequency alternating current. The high-frequency current is carried in a water-cooled copper coil called an inductor. The rapidly alternating magnetic field established within the loop of the coil induces current (I) within the steel. The induced current then generates heat (H) according to the relationship, $H = I^2 * R$, where R is the electrical resistance of the steel. The depth of heating produced by induction is inversely related to the frequency of the alternating current. The higher the frequency the thinner, or more shallow, the heating. Therefore, surface hardening is achieved by high frequencies, while through-hardening is produced by using lower frequencies.

There are two methods that can be used to produce monolithic dual hardness gradient material. One is induction tempering and the other is induction rehardening. The induction tempering method will produce a plate in which the change of hardness from high to low will be more drastic than the induction rehardening method. When an induction tempering method is used, the tempering temperatures will affect the level of the hardness gradient of the back face (softer side). A tempering temperature of 925° F as compared to 425° F will produce a hardness profile that more closely represents the gradient in a standard rolled bonded dual hard armor steel.

It is anticipated that the successful completion of Phase I and Phase II will generate a material and process to complement conventional dual hard armor steels for use as an applique armor on light- to medium-weight military vehicles (high-mobility, multipurpose wheeled vehicle [HMMWV]; light assault vehicle [LAV]; Bradley class) as applique armor.

4. PROCEDURE

The following procedure was developed in this study:

Phase I

1. Obtain and characterize rolled bonded material from Jessop Steel Company (JSC).
2. Ballistically test the material.
3. Determine the problem areas of rolled bonded material.

4. Determine the thickness percentage of hard material vs. soft material in JSC-produced dual hard material.
5. Produce heats (at ARL/MD) with the same chemical composition.
6. Produce monolithic dual hard material using the induction heat-treating equipment (TOCCO).
7. Ballistically test the monolithic material.
8. Compare results.
9. Adjust parameters (chemical composition) and produce more ARL/MD in-house heats. Modify the procedures using the TOCCO Unit. Return to Step 7.

5. RESULTS/DISCUSSION

Dual hard steel armor plate from JSC was received and characterized. The hardness profiles were determined on six plates as a reference point for processing the monolithic plate (see Figures 1 and 2). The thickness of the hard side (~Rc 58) of the rolled bonded plate, not including the transition zone, ranged from 36 to 44% with an average and also a median of 40%. Plates from JSC (conventional rolled bonded material) were ballistically tested at ARL/MD with the 0.30-cal. AP M2 and 0.50-cal. AP M2 projectiles according to MIL-A-46099. The results are listed in Table 1. Table 1 also contains some ballistic data from the Heiss-Isenstaht (H-S) Ballistic Laboratory, Detroit, MI (Nongovernment range). Plates ballistically tested with the 0.30-cal. AP M2 projectile exhibited no outstanding problems. Problems, however, were encountered with those plates that were ballistically tested with the 0.50-cal. AP M2 projectile. Photographs (see Appendix B) were taken of the plates after they were shot. As can be seen from the pictures, three out of four plates that were tested at ARL/MD against the 0.50-cal. AP M2 projectile shattered. The plates delaminated between the hard and soft interface. This condition provides no multihit capability against the 0.50-cal. AP M2 threat. The armor plate thickness range for the 0.50-cal. AP M2 projectile per MIL-A-46099 is 0.3126–0.625 in. Delamination within this thickness range is the problem area that this study will be focused on.

In-house heats were produced for processing as listed in Table 2. Plates from heat 4353 were used to develop the best settings. Four trials were preformed.* Using the best trial, four plates were induction

* The processing parameters for producing the desired hardness gradient are intentionally left out of this report due to its proprietary significance to the U.S. Government.

tempered: two plates with a 725° F body temper and two plates with a 825° F body temper. The results of the ballistic testing (tested in accordance with MIL-A-46099) are listed in Tables 3 and 6.

A hardness profile thickness of approximately 40% was attempted. The hardness level was approximately Rc 55. Due to the lower-than-normal carbon content of this heat, the hardness level was limited. This heat was used only for trial and error in developing the required induction unit processing controls for developing monolithic armor plate with approximately the same characteristics of the rolled bonded material. Ballistically, the four plates did not meet the specification; however, the plates did not shatter as did the rolled bonded material against the 0.50-cal. AP M2 projectile. Photographs of the ballistically tested plates are shown in Appendix C. Multihit capability is evident.

The second heat to be processed was Z-62A first pour. Its carbon level was 0.56% (see Table 2 for the complete chemistry), and therefore, a higher hardness could be obtained. The first seven plates of the heat were induction tempered: two plates with a 425° F body temper, two plates with a 825° F body temper, and three plates with a 950° F body temper. The hardness profiles were varied for each plate and are plotted in Figures 3, 4, and 5. The results of the ballistic test are listed in Tables 4 and 6. Appendix D shows photographs of the ballistically tested plates. Multihit capability is again evident. The cracks on some of the plates were due to the holding fixture adding excessive stress to the plate. The ballistic test for plate No. 2B was terminated because complete penetrations as low as 2,660 ft/s were occurring. As can be seen from Figure 3, the hardness profile is suspect.

Table 6 indicates that an armor plate with approximately a 40% front face at Rc 60, a back face of approximately Rc 51, and a tempering temperature of 425° F gave results comparable to conventional rolled bonded dual hard armor plate.

The next series of tests included 16 plates from the same heat, i.e., Z-62A, first pour (see Table 5). Two tempering temperatures, 925° F and 425° F, were used. Tempering temperatures will affect the level/type of the hardness gradient of the back face (softer side). Various gradients with respect to depth were produced, ranging from 31 to 48% for the front face. The hardness of the front face was held at approximately Rc 60. The hardness of the back face was varied from Rc 42.6 to Rc 52.5. The results of these 16 plates are summarized in Table 7. Four acceptable (with respect to the ballistic requirements of MIL-A-46099) plates were observed. The hardness profiles of these 16 plates are plotted in Figures 6,

7, 8, and 9. Photographs of the ballistically tested plates are shown in Appendix E with the multihit capability again being evident.

An attempt was undertaken to determine why 4 plates passed and 12 plates failed the ballistic requirements. However, a detailed explanation could not be documented. One thing is known, however—the higher hardness (front face) must be consistent across the face for a certain thickness. This thickness will vary in accordance with several factors, such as the actual hardness level of the front face, the gradient of the softer side (back face), and the level of hardness of the back face. If the hardness gradient of the back face is the same hardness and consistent (as in the case of a plate tempered at 925° F), then the thickness of the front face must be greater than a plate that has a back side gradient that increases in hardness over the width of the back side thickness. This can be seen in plate No. 14. The opposite of this is also true. That is, if the back side has an increasing hardness gradient (425° F temper), then the thickness of the front face can be reduced, as in the case of plate No. 15. The problem that exists is that all the plates that were processed and tested do not have a "black-and-white" phenomenon that can explain why certain plates pass and others fail the ballistic test. Such is the case with plate Nos. 20 and 15. The hardness levels, the hardness gradient for both the front face and the back face, the plate thickness, and the processing (same temper) were approximately the same for both plates. However, the ballistic results of the 2 plates vary by 181 ft/s.

Further testing is required and will be accomplished in Phase II. Phase I demonstrated that induction heat treating is a viable method for producing monolithic gradient hard armor steel plate that can complement standard dual hard rolled bonded steel armor.

6. CONCLUSIONS

(1) Phase I efforts have demonstrated that the technique of induction heat treating can produce a monolithic steel armor plate with a hardness gradient that passes the ballistic requirements of MIL-A-46099.

(2) Based on the results obtained in Phase I, the following chemical composition should be used as a starting point for Phase II:

Carbon \approx 0.58% - 0.60%
Manganese \approx 0.44%
Silicon \approx 0.35%
Nickel \approx 3.28%
Chromium \approx 0.61%
Molybdenum \approx 0.45%

7. RECOMMENDATIONS

(1) Based on the ballistic data obtained in Phase I, it is recommended that the Induction Heat Treat Program continue with Phase II.

(2) The heats developed during Phase I (see Table 2) but not utilized along with six other heats that are currently being produced should be utilized in Phase II. Phase II will optimize the chemical composition, the hardness levels, the thickness of these hardness levels (front face and back face), and the gradient of the back face. The gradient of the front face will be held constant (i.e., the hardness level of the front face will be the same across the front face thickness).

Table 1. Ballistic Testing of Rolled Bonded Dual Hard Material

Threat: 0.50-cal. AP M2				
Jessop Plate No.	Firing Record	Thickness (in)	Obliquity	V ₅₀ (ft/s)
K2230-8	040-94	0.382	0	2,305
K2221-4	037-94	0.528	0	2,365
K2221-3	H-S Lab	0.528	0	2,446
K2230-8	041-94	0.382	30	2,560
K2230-7	H-S Lab	0.382	30	2,595
K2221-4	042-94	0.528	30	2,776
Threat: 0.30-cal. AP M2				
K2216-4	044-94	0.267	0	2,342
SDH No. 1	020-94	0.335	0	2,283
K2216-3	043-94	0.269	30	3,080
SDH No. 2	021-94	0.342	30	3,263

Table 2. Chemistries of In-House Heats

Heat No.	C	Mn	SI	NI	Cr	Mo	P	S
4353	0.530	0.89	0.30	1.99	0.83	0.25	0.002	0.002
Z-60A/1	0.597	0.33	0.30	3.24	0.97	0.52	0.007	0.018
Z-60A/2	0.629	0.44	0.45	3.12	0.62	0.49	0.014	0.010
Z-60A/3	0.638	0.35	0.36	3.51	0.58	0.48	0.006	0.012
Z-61A/1	0.622	1.42	1.34	2.47	0.82	0.53	0.011	0.003
Z-61A/3	0.663	1.48	1.34	2.56	0.93	0.57	0.006	0.008
Z-61A/4	0.622	1.29	1.19	2.57	0.84	0.56	0.009	0.011
Z-62A/1	0.560	0.44	0.35	3.28	0.61	0.45	0.007	0.003
Z-62A/2	0.554	0.35	0.32	3.00	0.53	0.43	0.010	0.013

Table 3. Ballistic Testing of Monolithic Dual Hard Material Heat No. 4353

Threat: 0.50-cal. AP M2					
ARL/MD Plate No.	Temper (° F)	Firing Record	Thickness (in)	Obliquity	V ₅₀ (ft/s)
53-1	725	067-94	0.543	30	2,908
53-2	725	070-94	0.554	0	2,292
53-3	825	069-94	0.550	0	2,425
53-4	825	068-94	0.549	30	2,910

Table 4. Ballistic Testing of Monolithic Dual Hard Material Heat No. Z-62A/1

Threat: 0.50-cal. AP M2					
ARL/MD Plate No.	Temper (° F)	Firing Record	Thickness (in)	Obliquity	V ₅₀ (ft/s)
Z-62-1A	425	0118-94	0.536	30	2,956
Z-62-1B	425	0122-94	0.523	30	2,851
Z-62-2A	950	0123-94	0.546	30	2,930
Z-62-2B	950	0121-94	0.518	30	No Test ^a
Z-62-2C	950	0120-94	0.531	30	2903
Z-62-3A	825	0119-94	0.538	30	2902
Z-62-3B	825	0117-94	0.539	30	2847

^a Test was terminated due to all complete penetrations as low as 2,660 ft/s. See discussion for an explanation.

Table 5. Ballistic Testing of Monolithic Dual Hard Material Heat No. Z-62A/1

Threat: 0.50-cal. AP M2					
ARL/MD Plate No.	Temper (° F)	Firing Record	Thickness (in)	Obliquity	V ₅₀ (ft/s)
Z-62-5	925	0161-94	0.546	30	2,924
Z-62-6	925	0164-94	0.522	30	2,909
Z-62-15	425	0158-94	0.532	30	3,033
Z-62-17	425	0159-94	0.531	30	3,002
Z-62-18	425	0160-94	0.523	30	3,025
Z-62-22	425	0162-94	0.523	30	2,914
Z-62-23	425	0163-94	0.517	30	2,875
Z-62-13	925	0167-94	0.523	30	2,901
Z-62-7	925	0165-94	0.530	30	2,860
Z-62-21	425	0166-94	0.529	30	2,927
Z-62-19	425	0168-94	0.529	30	2,877
Z-62-20	425	0169-94	0.533	30	2,852
Z-62-11	925	0170-94	0.530	30	2,900
Z-62-1	925	0171-94	0.530	30	2,888
Z-62-8	925	0172-94	0.541	30	2,879
Z-62-14	925	0173-94	0.519	30	2,962

Table 6. Hardness Profile vs. Ballistics (0.50-cal. AP M2)^a

Heat and Plate No.	Temper (° F)	Thck (in)	Front Face - Rc ^b	% of Front Face	Back Face - Rc ^b	V ₅₀ (ft/s)	Pass/Fail (ft/s)
4353-1	725	0.543	55.5	38%	46.5	2,908	-86
4353-2	725	0.554	55.5	38%	46.5	2,292	-247
4353-3	825	0.550	55.5	38%	45.5	2,425	-100
4353-4	825	0.549	55.5	38%	44.0	2,910	-108
Z-62A/1-1A	425	0.536	60.3	40%	51.4	2,956	-11
Z-62A/1-1B	425	0.523	61.9	37%	50.7	2,851	-65
Z-62A/1-2A	950	0.546	60.1	29%	45.0	2,930	-76
Z-62A/1-2B	950	0.518	65.0	17%	44.5	—	Test Stopped
Z-62A/1-2C	950	0.531	62.1	37%	44.8	2,903	-45
Z-62A/1-3A	825	0.538	61.8	44%	51.1	2,902	-73
Z-62A/1-3B	825	0.539	61.6	37%	48.7	2,847	-132

^a All ballistic tests were performed at 30° obliquity, except for heat plate Nos. 4353-2 and 4353-3, which were performed at 0° obliquity. Also, the pass/fail values used for these two plates were calculated by using a mil handbook.

^b Hardness values are an average of all hardness readings taken at 0.01-in interval.

Table 7. Hardness Profile vs. Ballistics (0.50-cal. AP M2) at 30° Obliquity

Heat and Plate No.	Temper (° F)	Thck (in)	Front Face - Rc ^a	% of Front Face ^a	Back Face - Rc	V ₅₀ (ft/s)	Pass/Fail (ft/s)
Z-62A/1-5	925	0.546	59.6	38	43.1	2,924	-82
Z-62A/1-6	925	0.522	59.2	31	42.6	2,909	-3
Z-62A/1-15	425	0.532	59.5	32	51.5	3,033	+77
Z-62A/1-17	425	0.531	60.9	43	50.8	3,002	+50
Z-62A/1-18	425	0.523	60.1	38	52.5	3,025	+109
Z-62A/1-22	425	0.523	62.4	35	51.8	2,914	-2
Z-62A/1-23	425	0.517	61.9	36	51.3	2,875	-17
Z-62A/1-13	925	0.523	59.6	48	44.4	2,901	-15
Z-62A/1-7	925	0.530	62.1	42	44.5	2,860	-84
Z-62A/1-21	425	0.529	59.9	37	51.5	2,927	-13
Z-62A/1-19	425	0.529	59.4	42	50.7	2,877	-63
Z-62A/1-20	425	0.533	60.3	31	51.4	2,852	-104
Z-62A/1-11	925	0.530	60.8	34	45.5	2,900	-44
Z-62A/1-1	925	0.530	60.3	31	45.7	2,888	-56
Z-62A/1-8	925	0.541	60.0	33	43.2	2,879	-109
Z-62A/1-14	925	0.519	61.4	43	45.1	2,962	+63

^a Hardness values are an average of all hardness readings taken at 0.01-in interval.

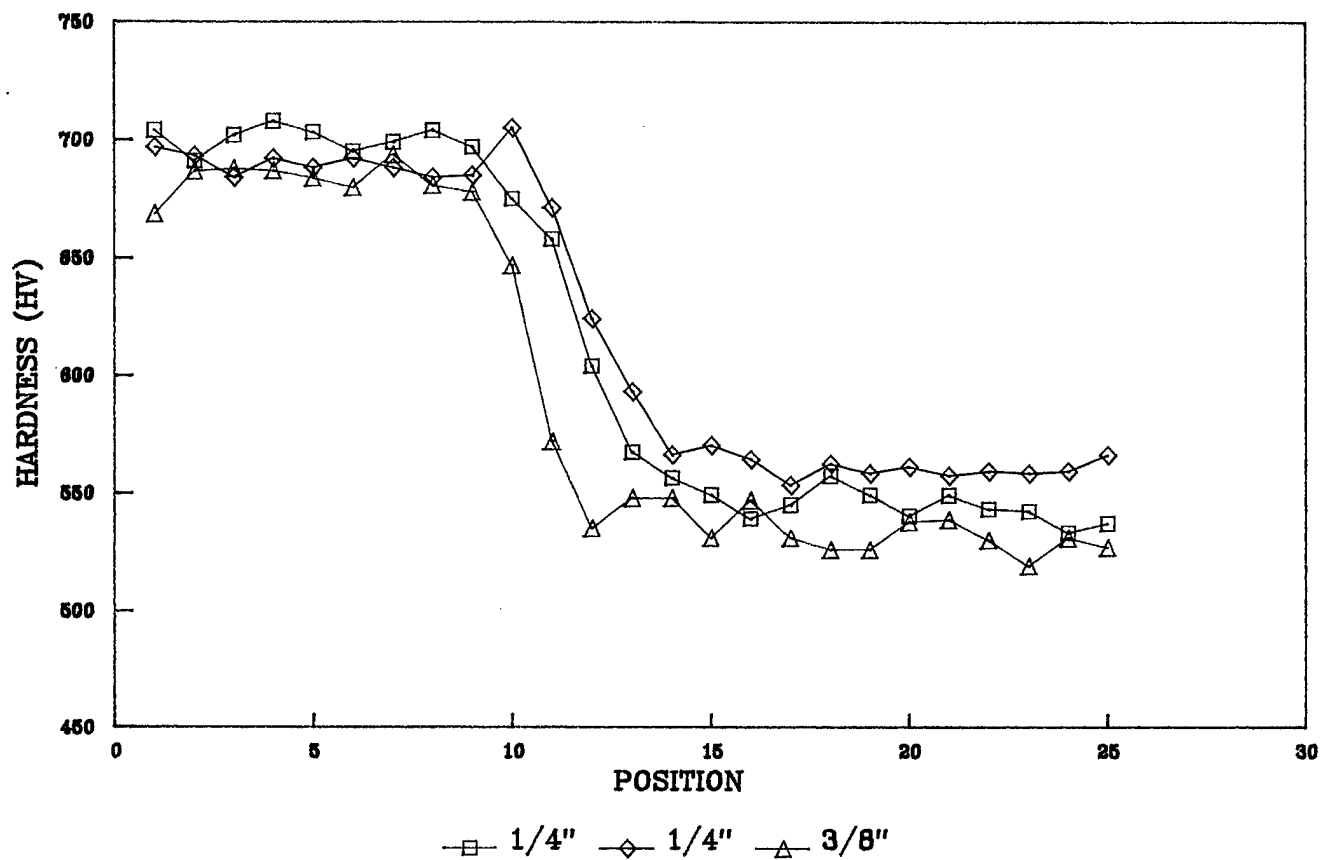


Figure 1. Standard dual hard Jessop steel.

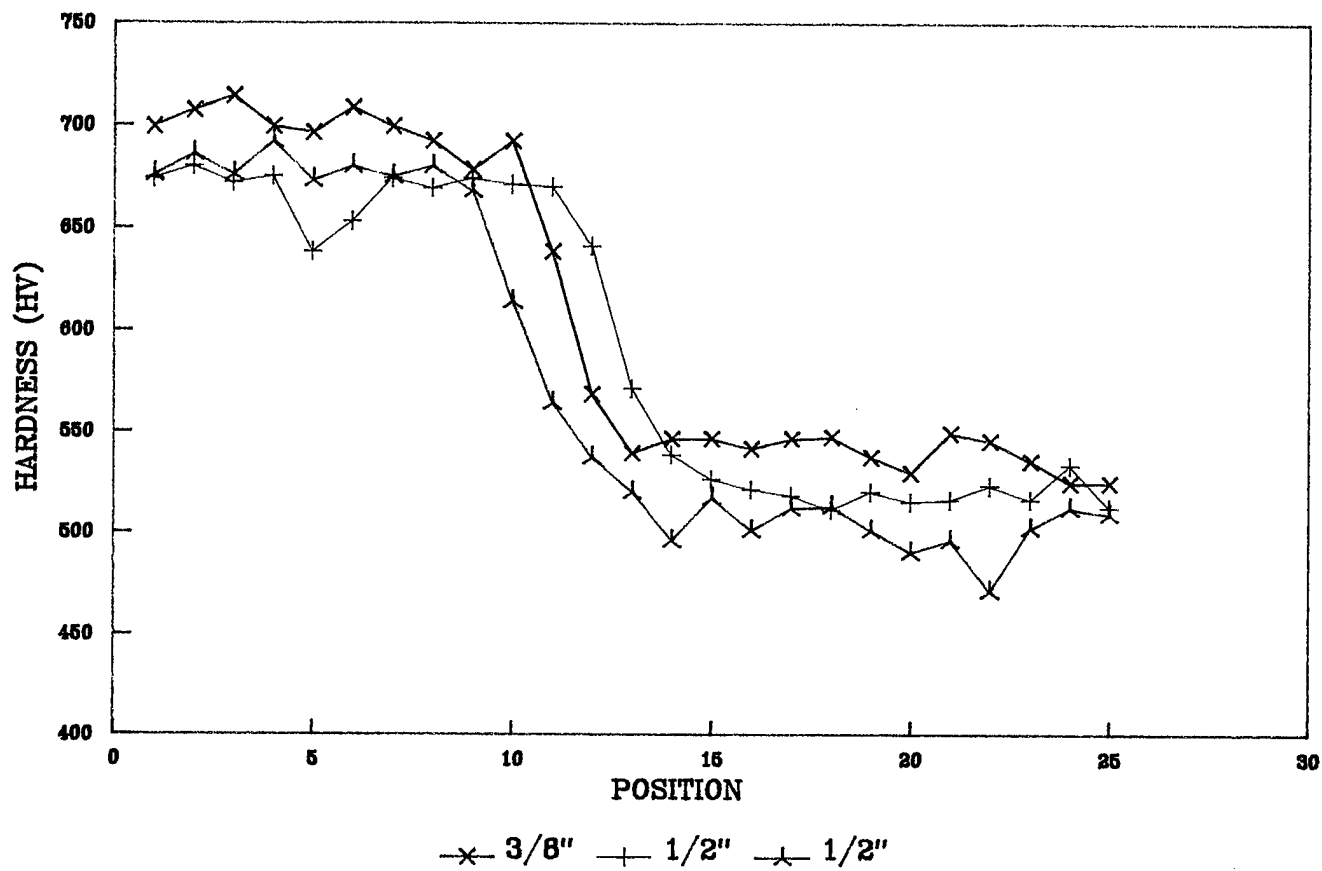


Figure 2. Standard dual hard Jessop steel.

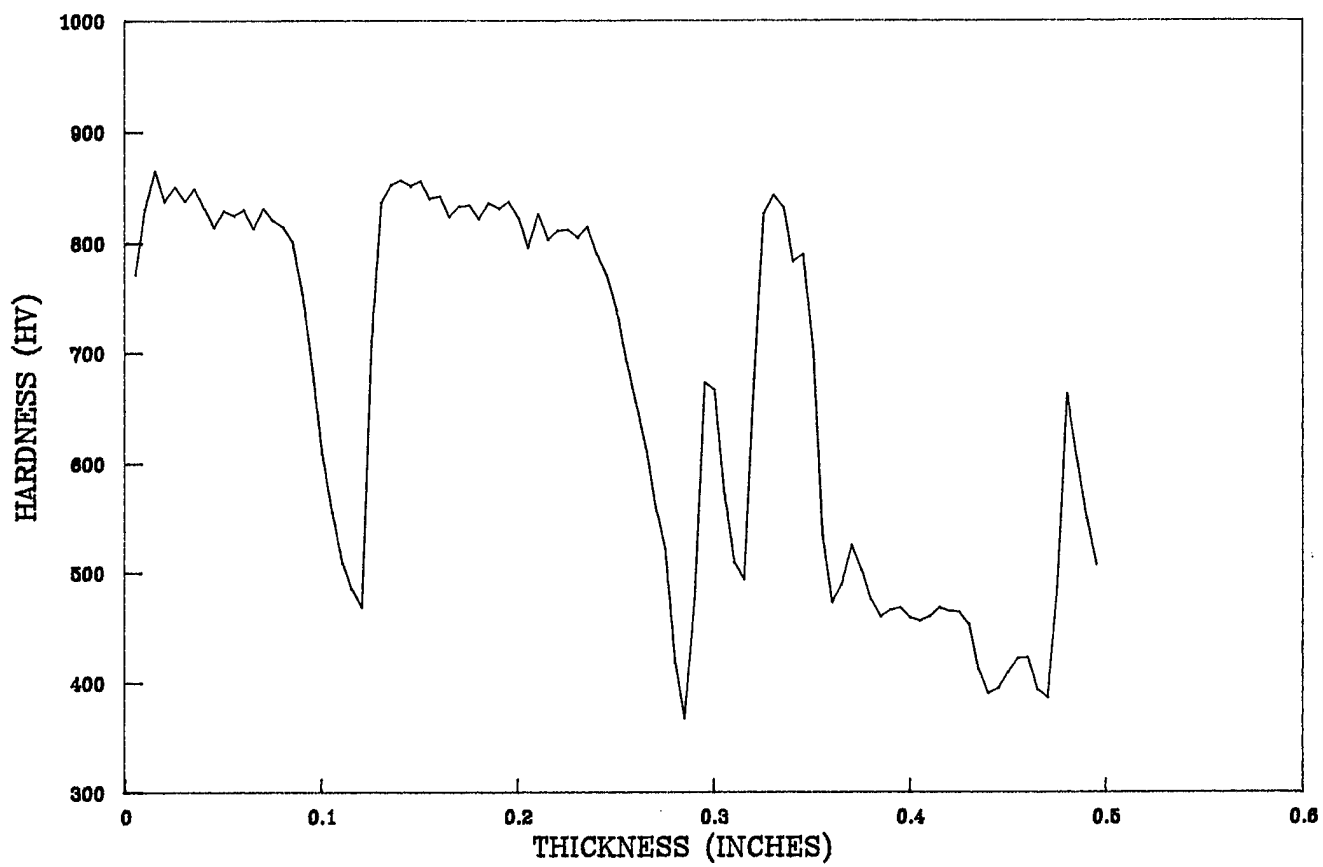


Figure 3. Heat No. Z-62A first pour - plate No. 2B.

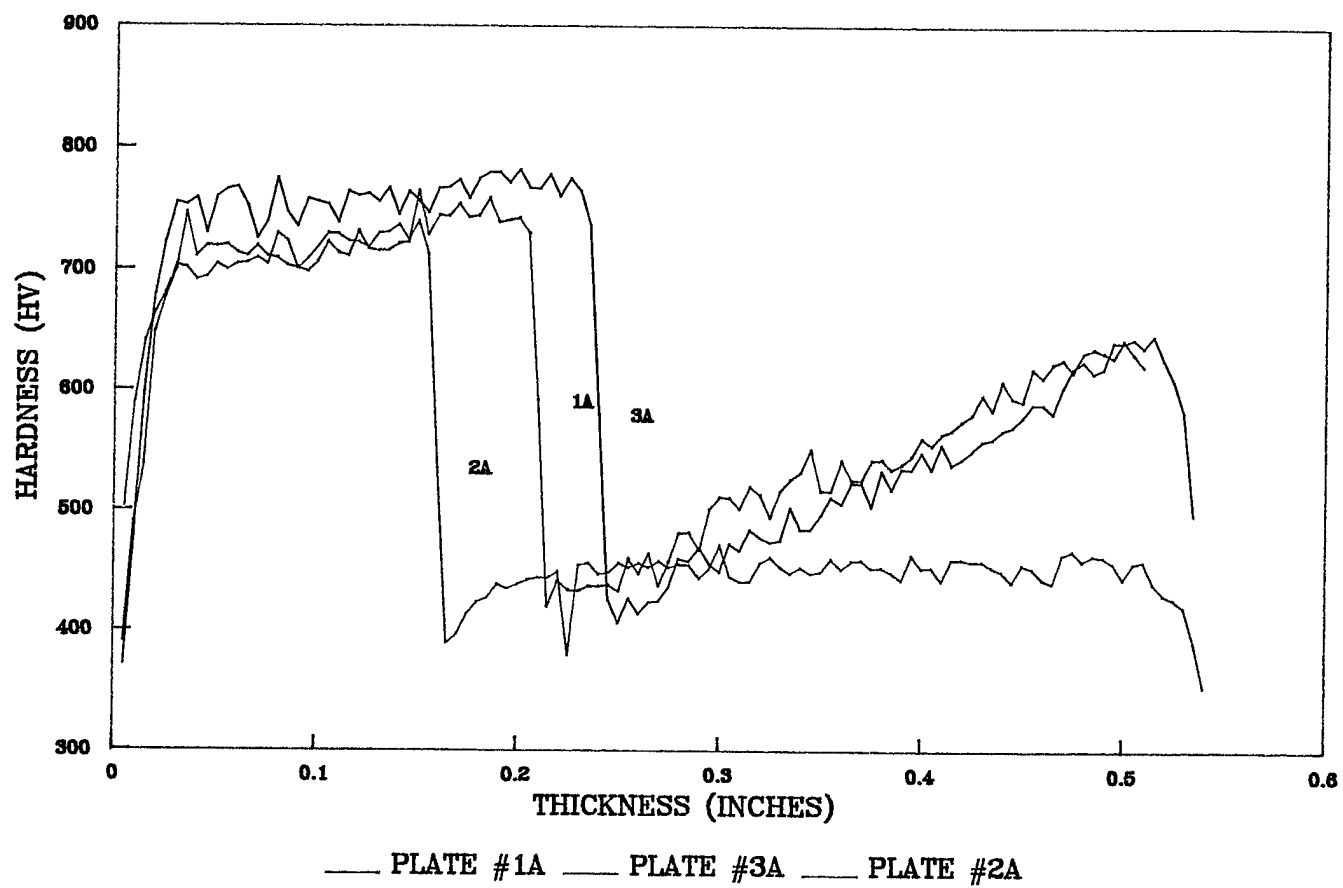


Figure 4. Heat No. Z-62A first pour - plate Nos. 1A, 2A, and 3A.

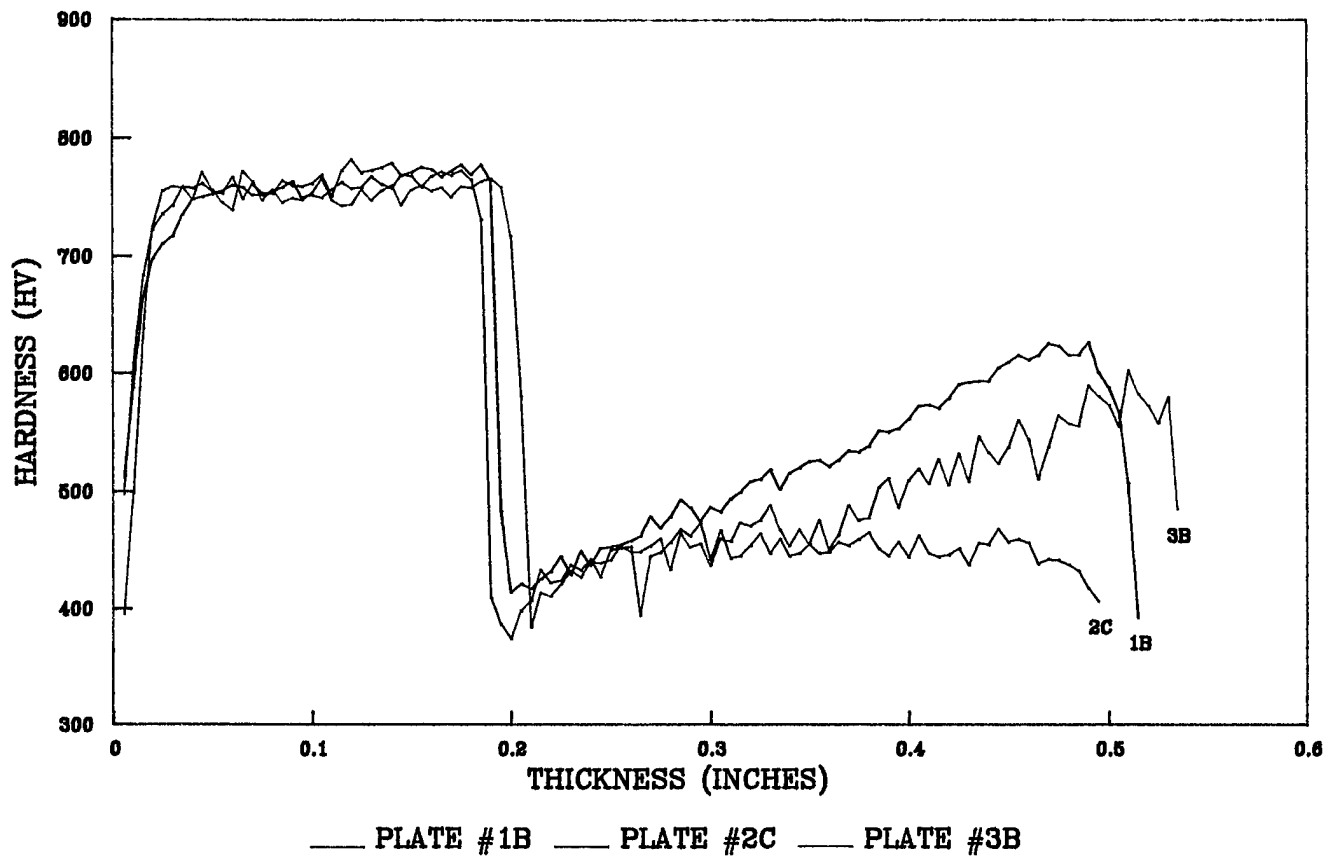


Figure 5. Heat No. Z-62A first pour - plate Nos. 1B, 2C, and 3B.

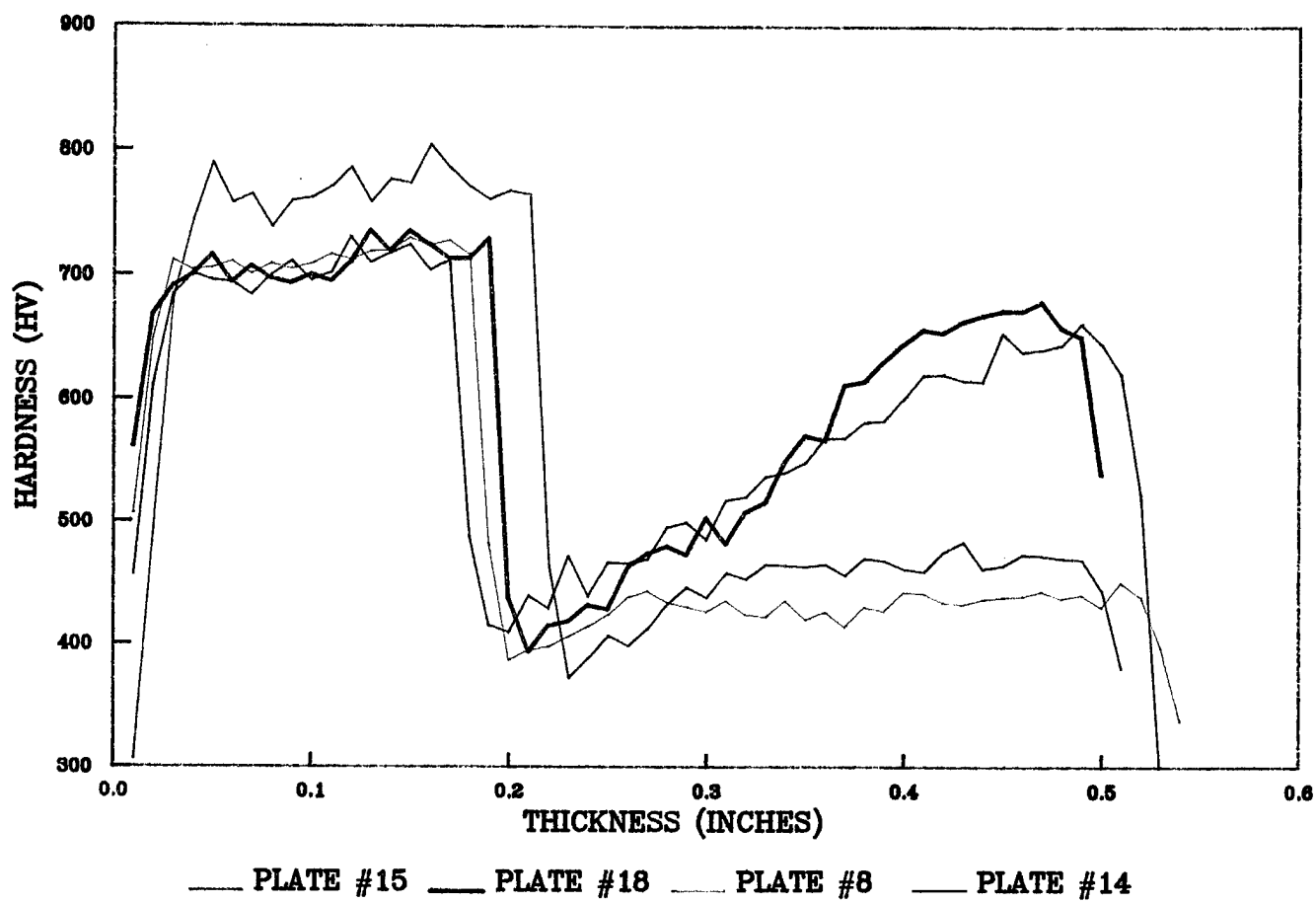


Figure 6. Heat No. Z-62A first pour - plate Nos. 15, 18, 8, and 14.

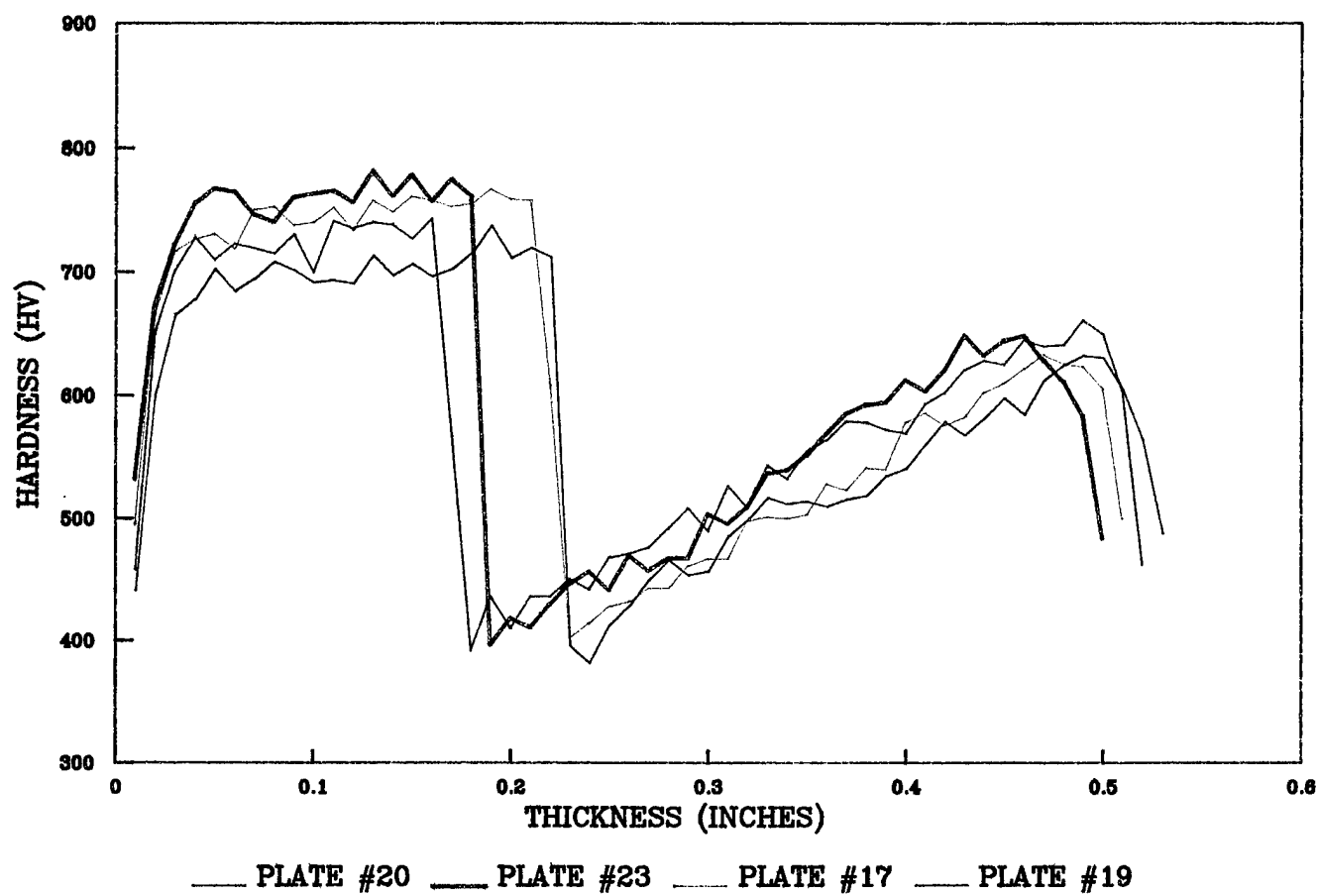


Figure 7. Heat No. Z-62A first pour - plate Nos. 20, 23, 17, and 19.

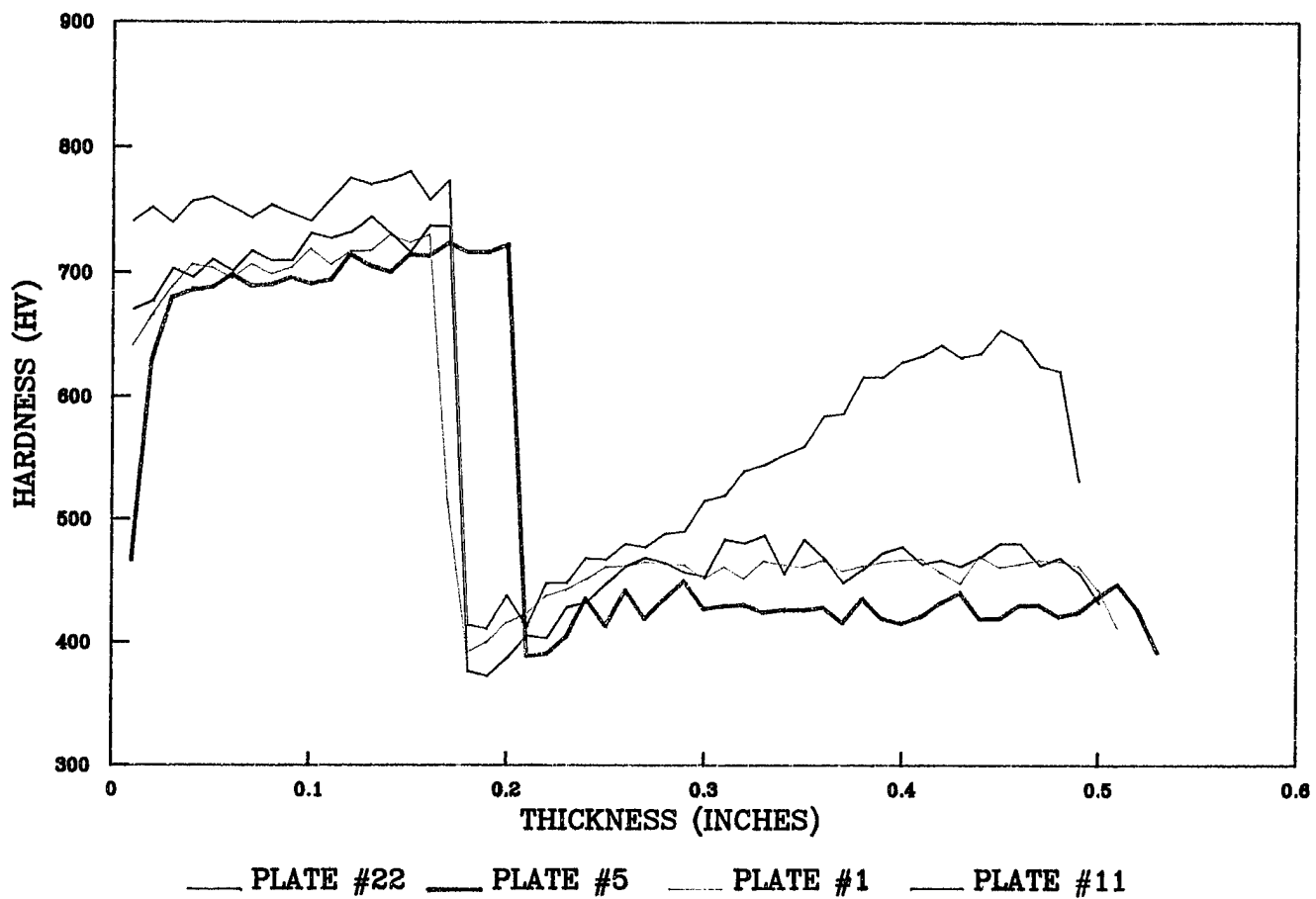


Figure 8. Heat No. Z-62A first pour - plate Nos. 22, 5, 1, and 11.

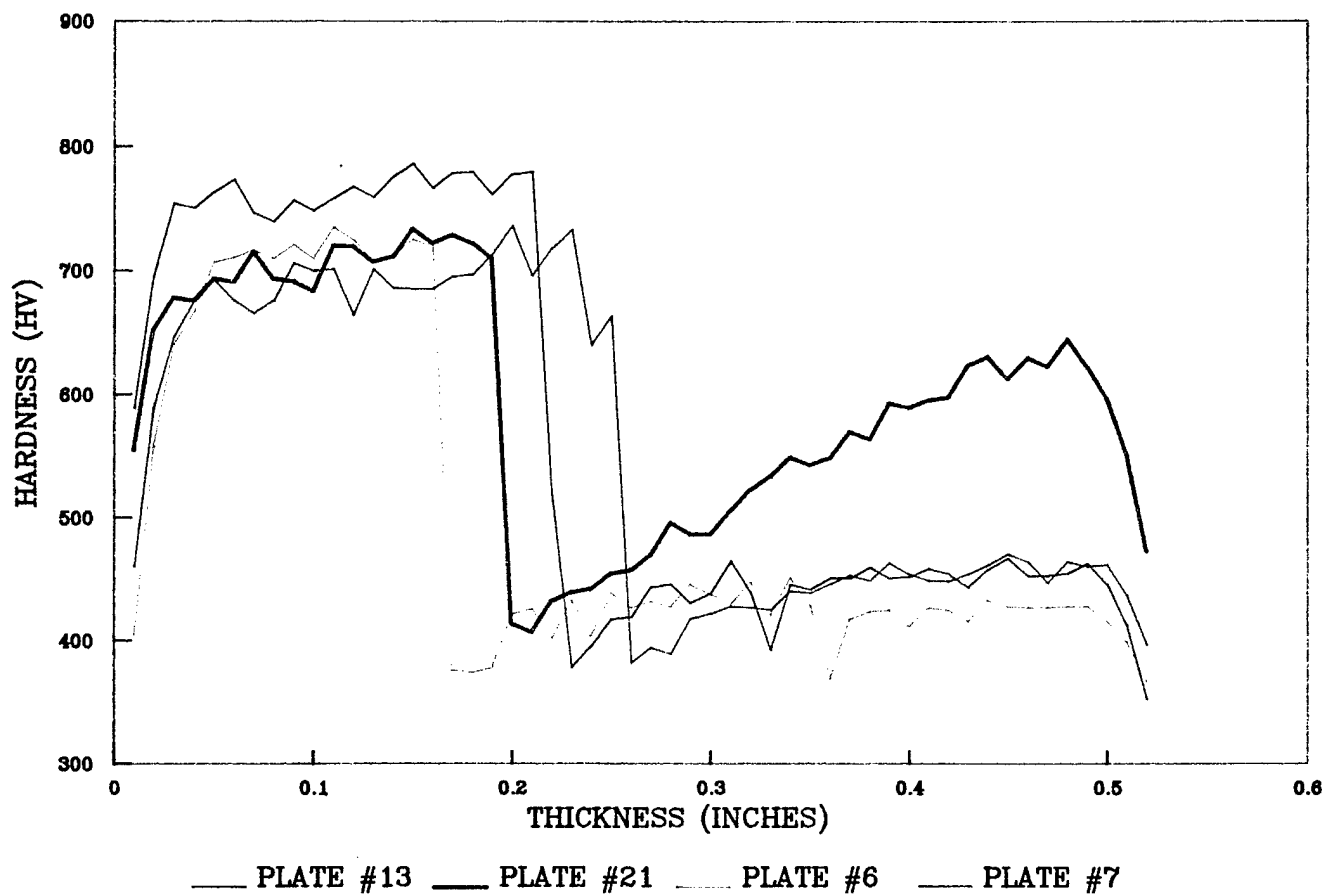


Figure 9. Heat No. Z-62A first pour - plate Nos. 13, 21, 6, and 7.

INTENTIONALLY LEFT BLANK.

APPENDIX A:
EQUIPMENT PHOTOGRAPHS

INTENTIONALLY LEFT BLANK.

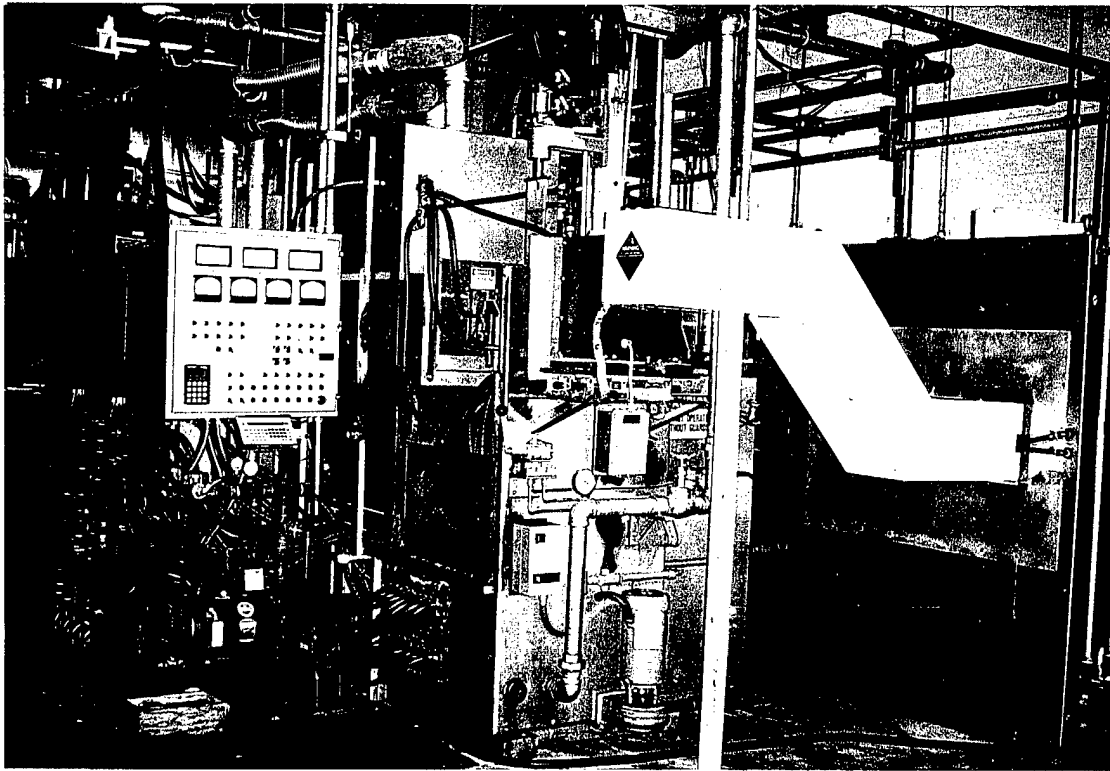


Figure A-1. Overall view of work station and controls with quench system and RF transformer.

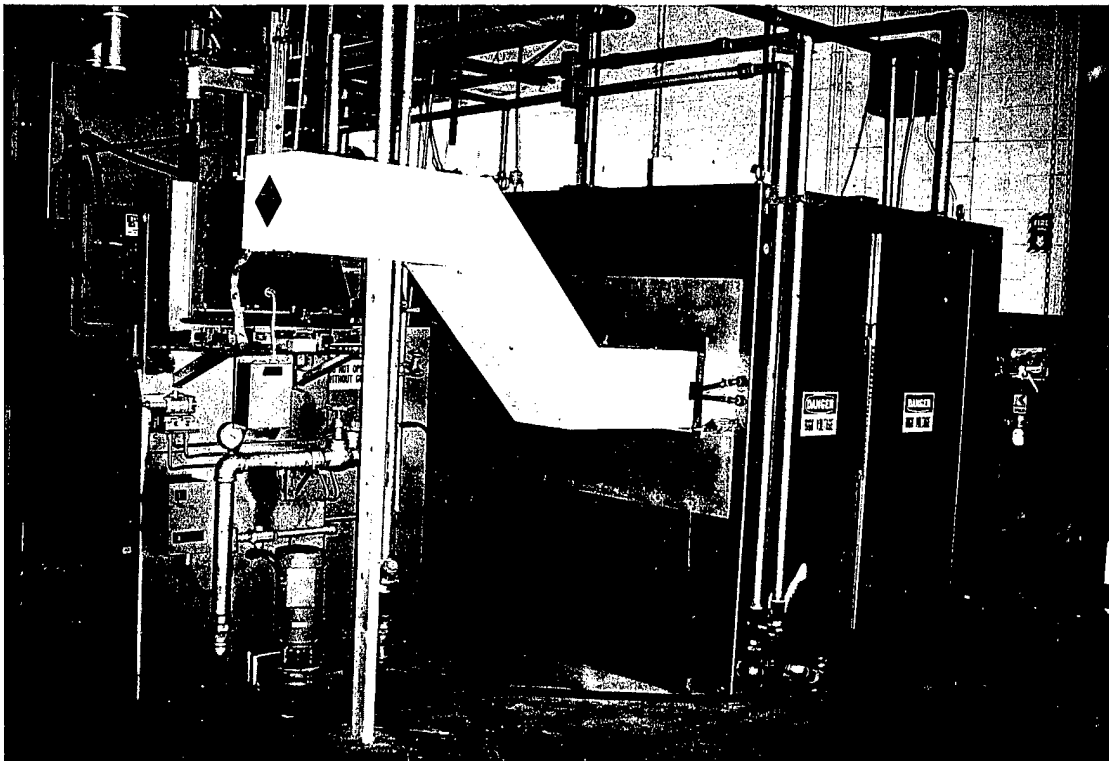


Figure A-2. RF power supply and RF transformer.

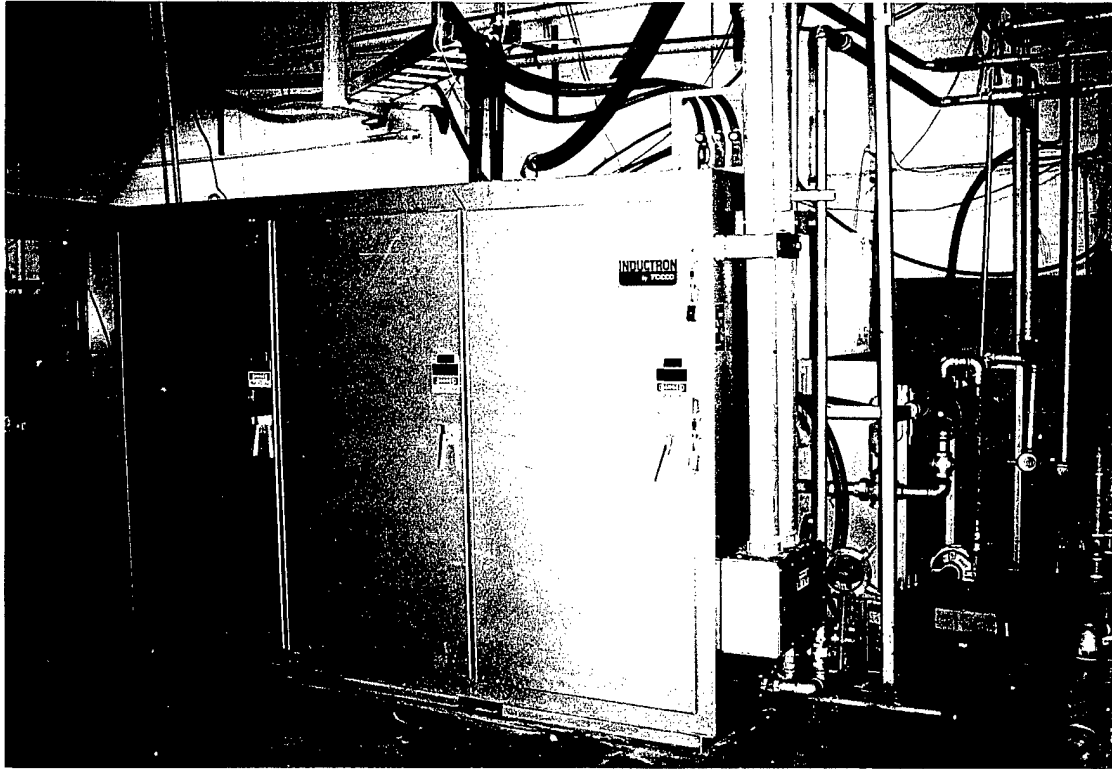


Figure A-3. AF power supply that feeds into the AF transformer.

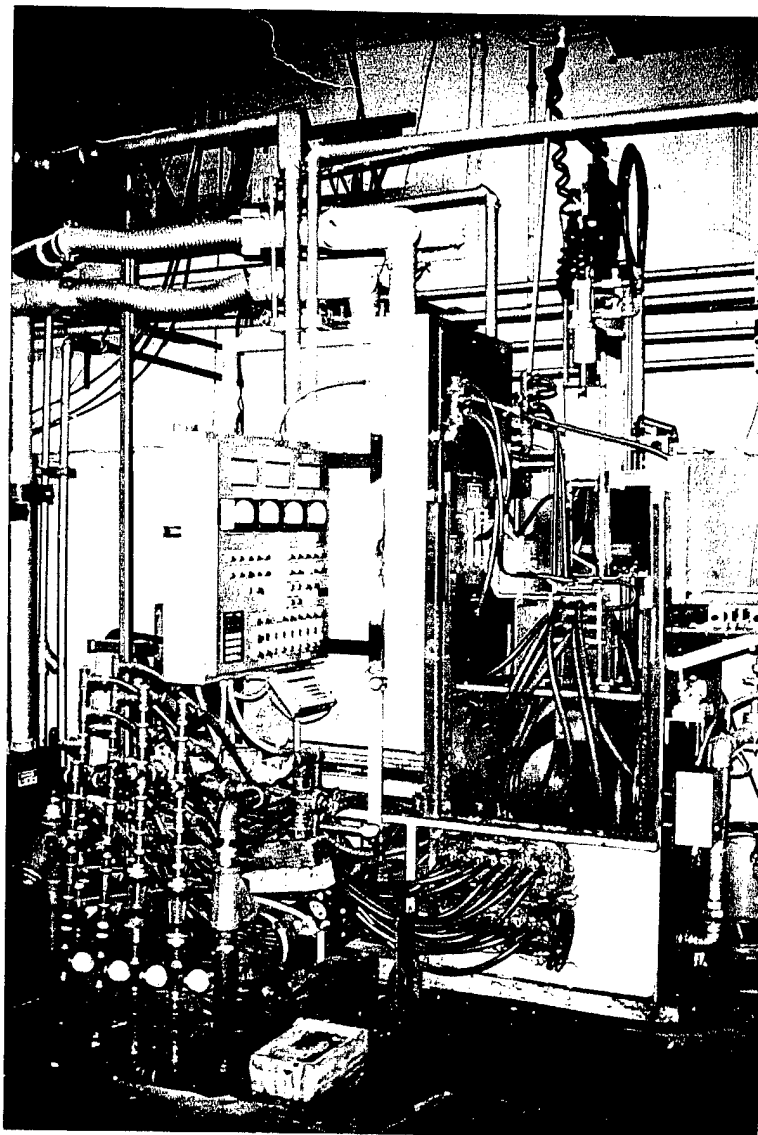
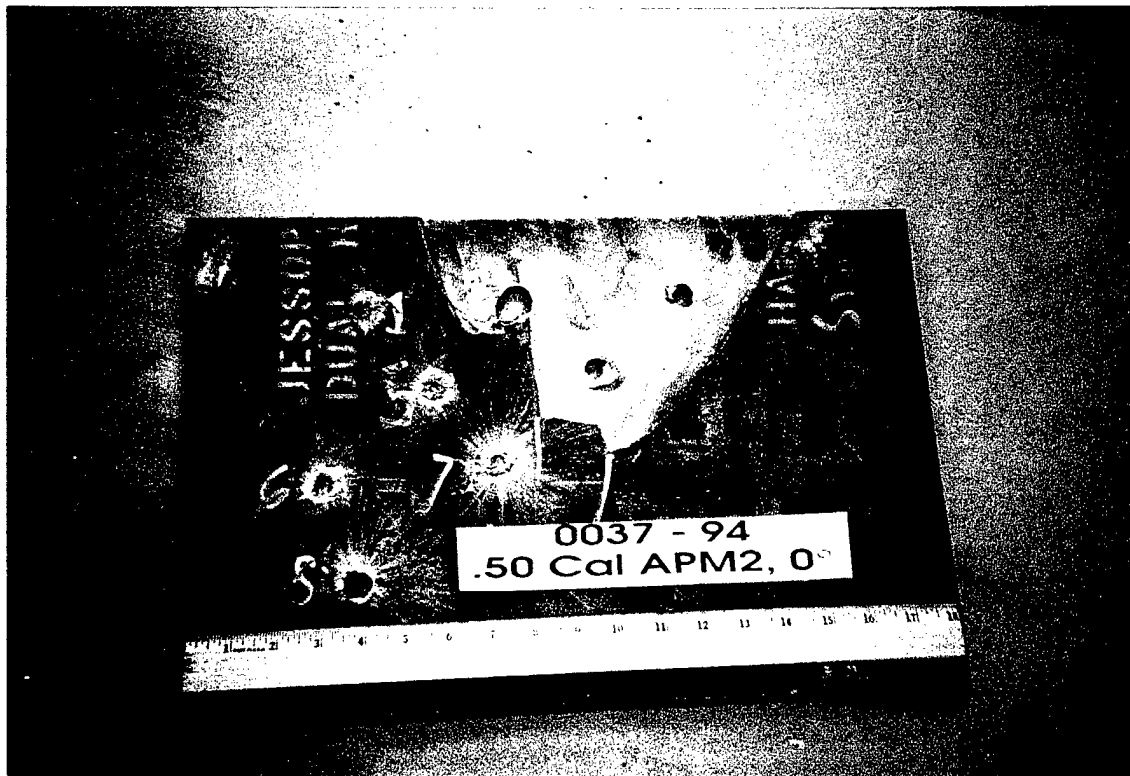


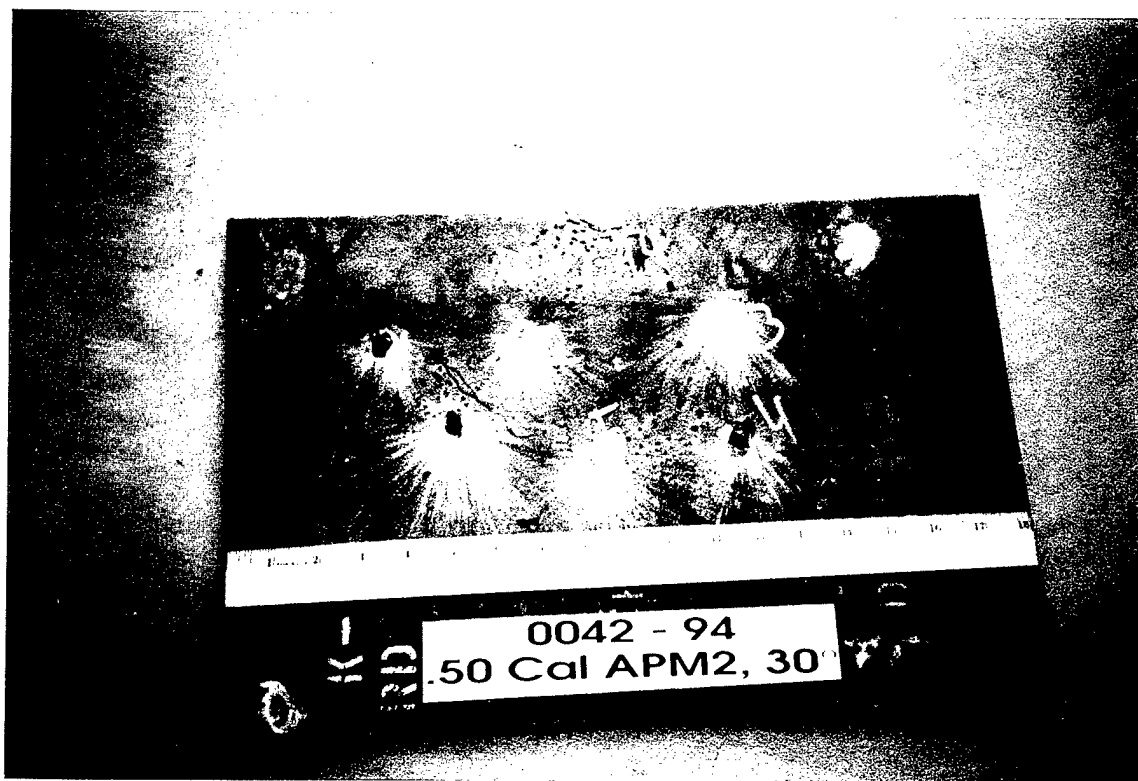
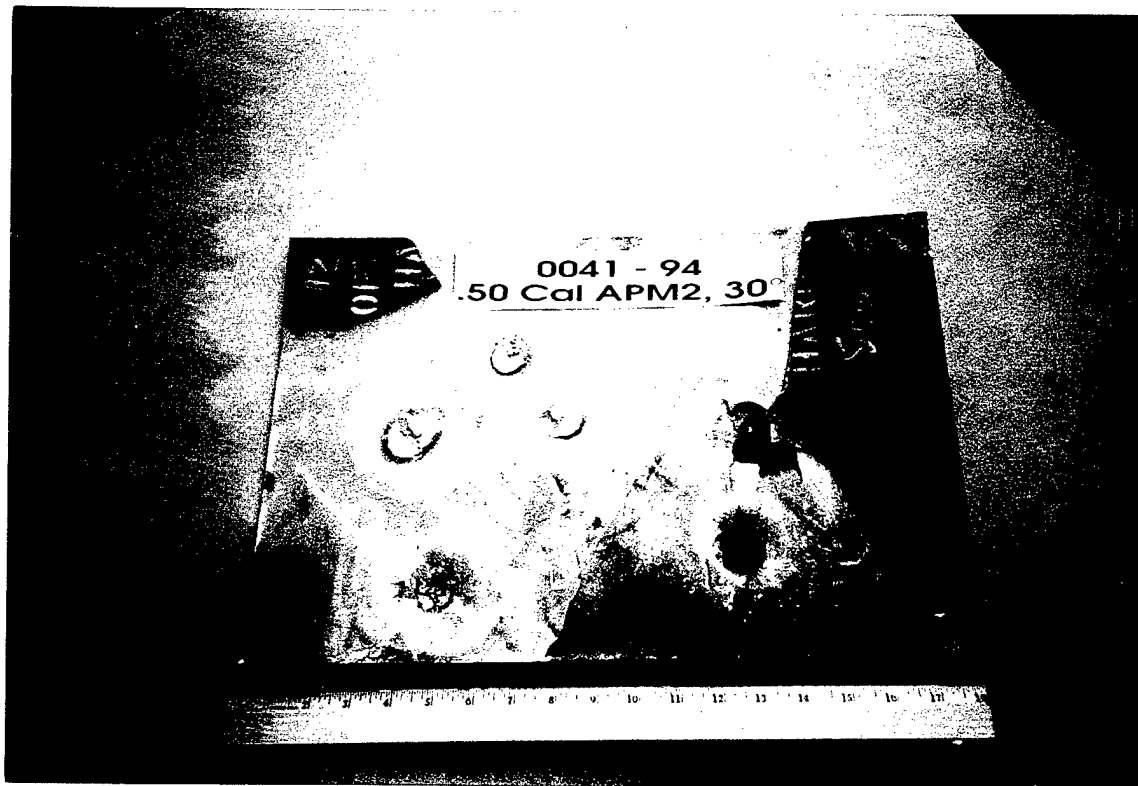
Figure A-4. AF transformer housing, station controls, and quench system.

INTENTIONALLY LEFT BLANK.

APPENDIX B:
PHOTOGRAPHS OF JESSOP STEEL CONVENTIONAL ROLLED BONDED MATERIAL

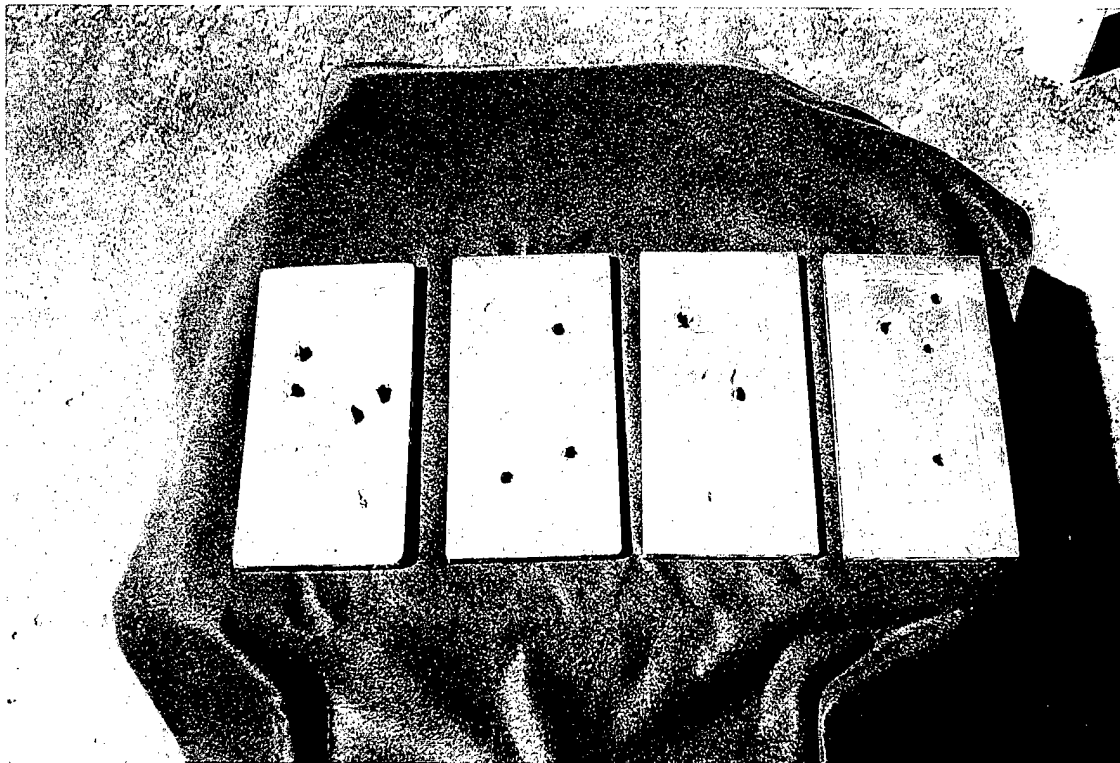
INTENTIONALLY LEFT BLANK.





APPENDIX C:
PHOTOGRAPHS OF HEAT NO. 4353

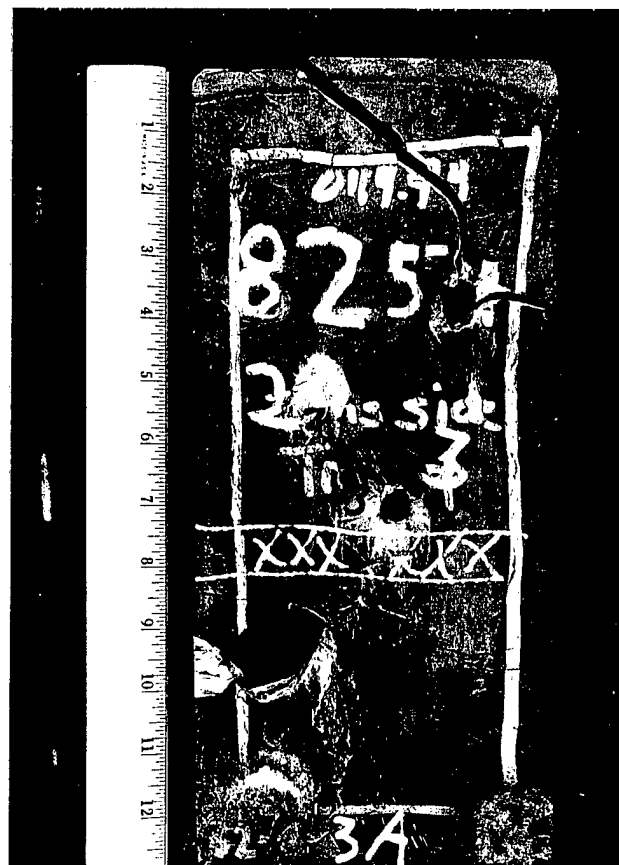
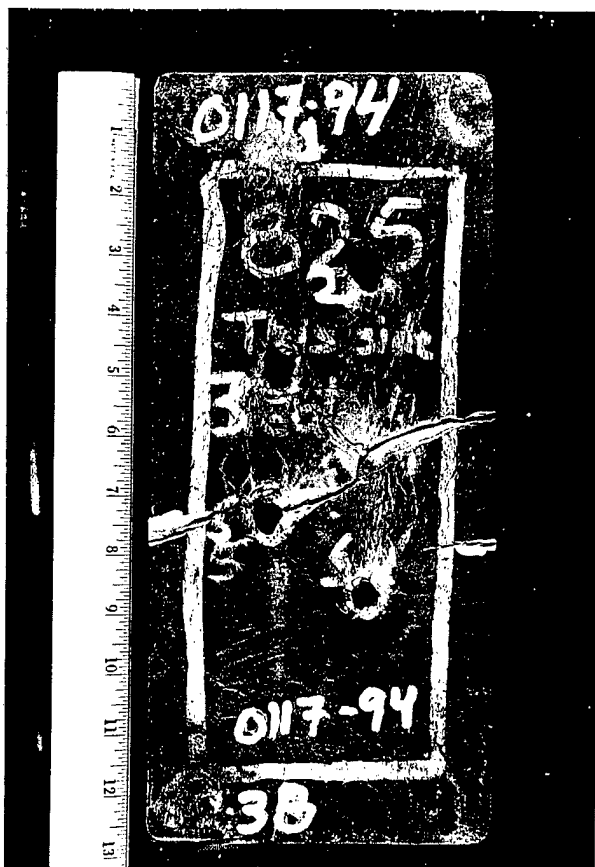
INTENTIONALLY LEFT BLANK.

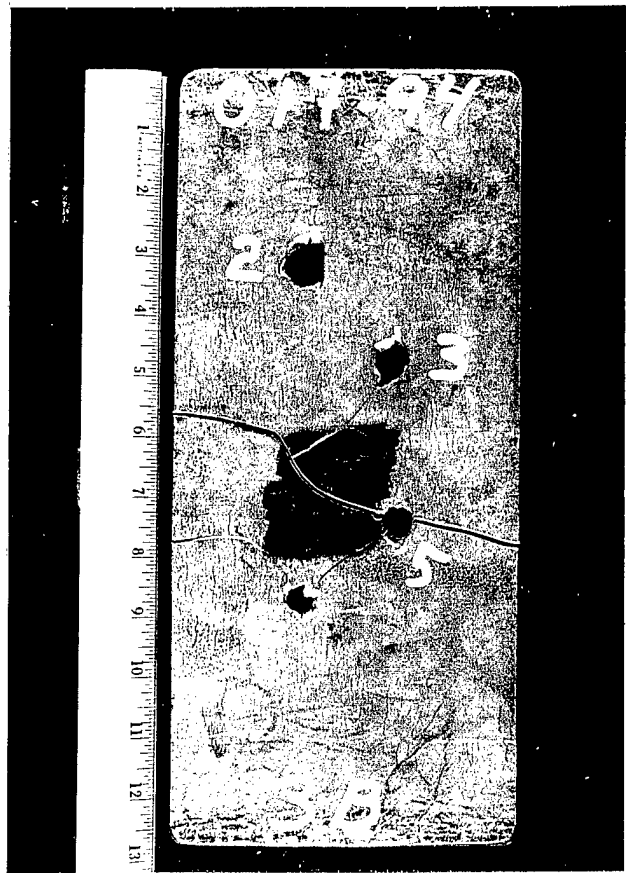


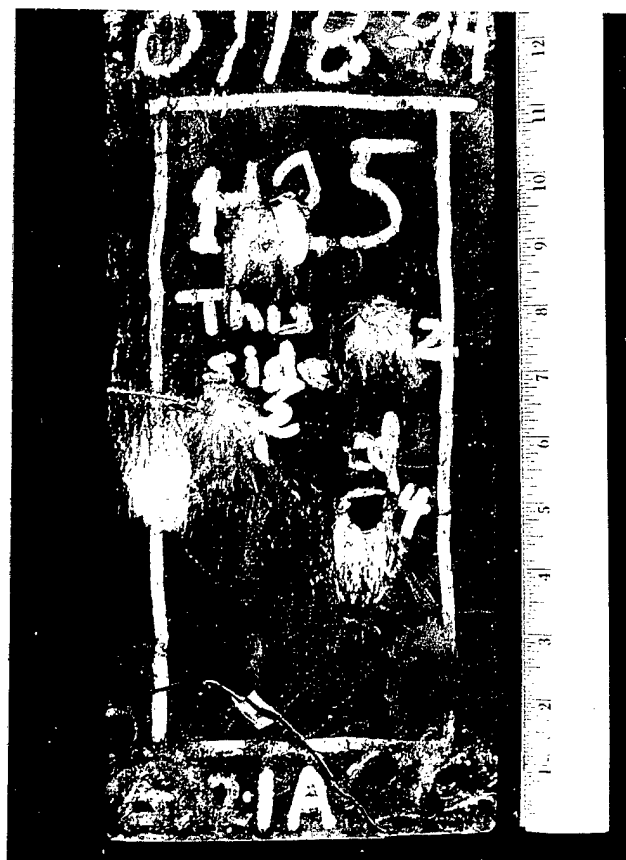
INTENTIONALLY LEFT BLANK.

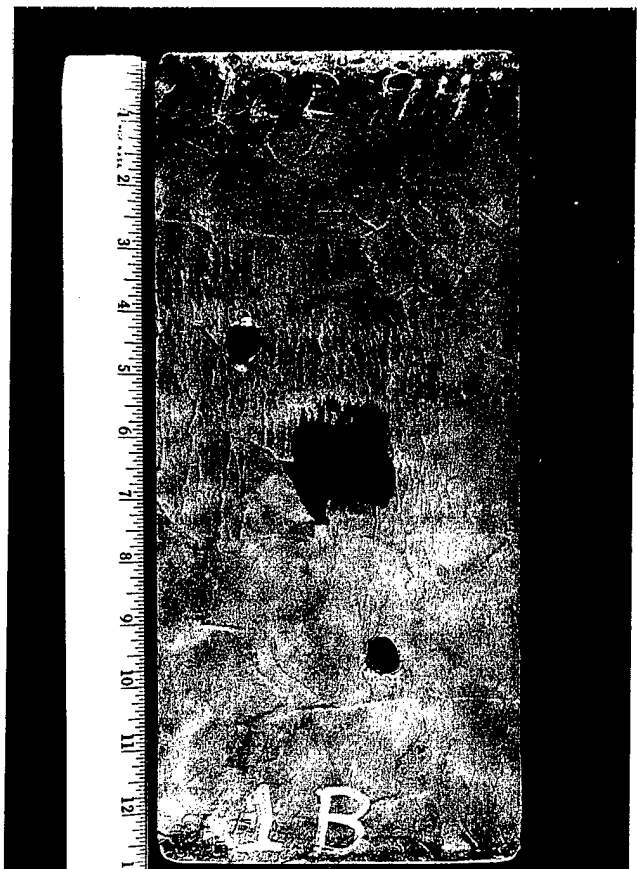
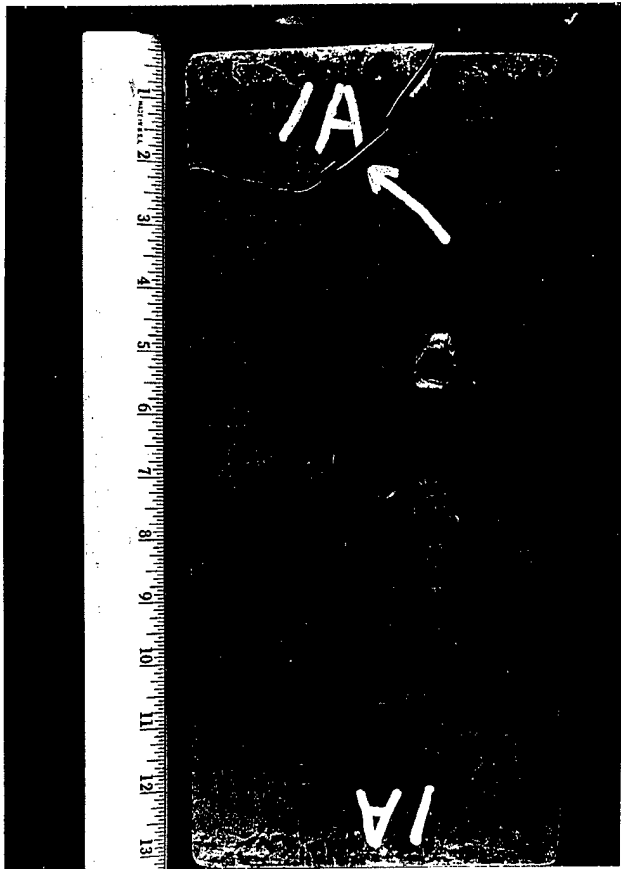
APPENDIX D:
PHOTOGRAPHS OF HEAT NO. Z-62A 1ST POUR

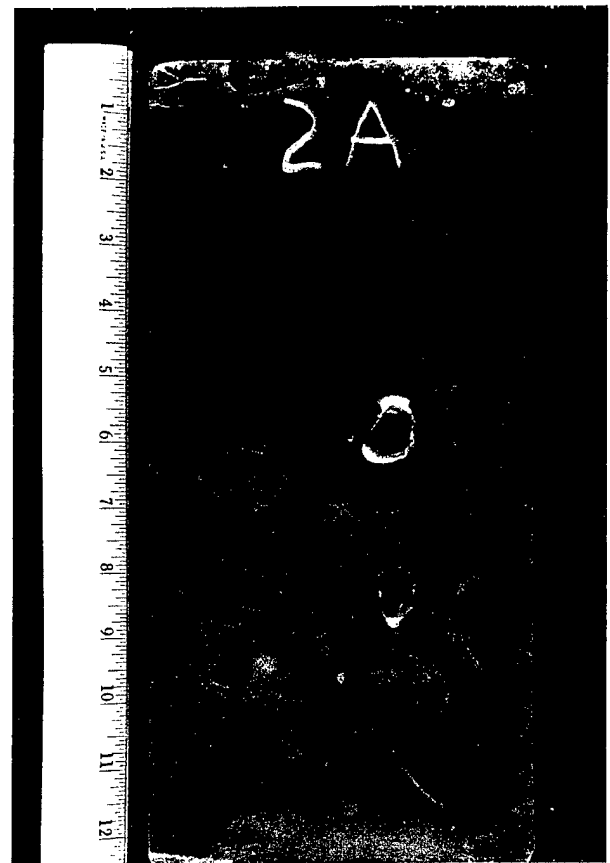
INTENTIONALLY LEFT BLANK.

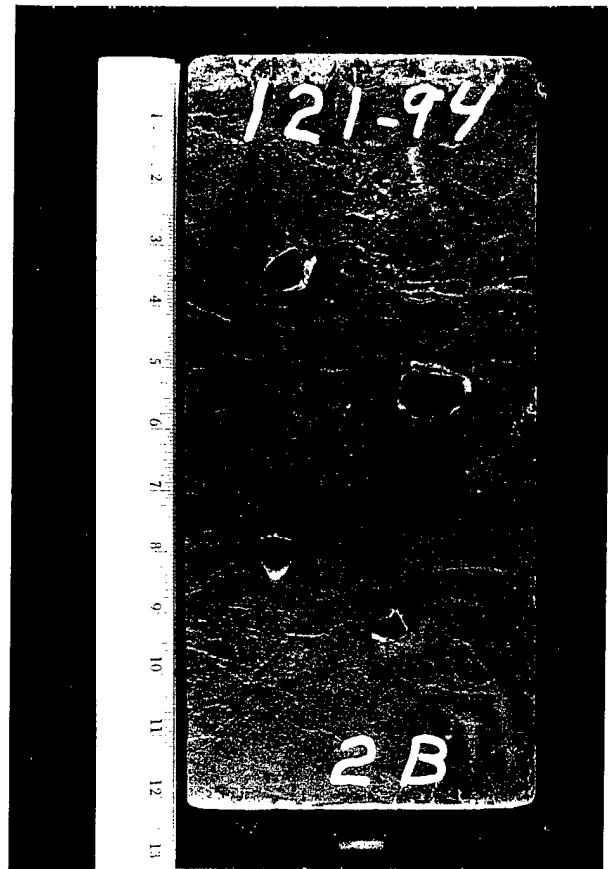


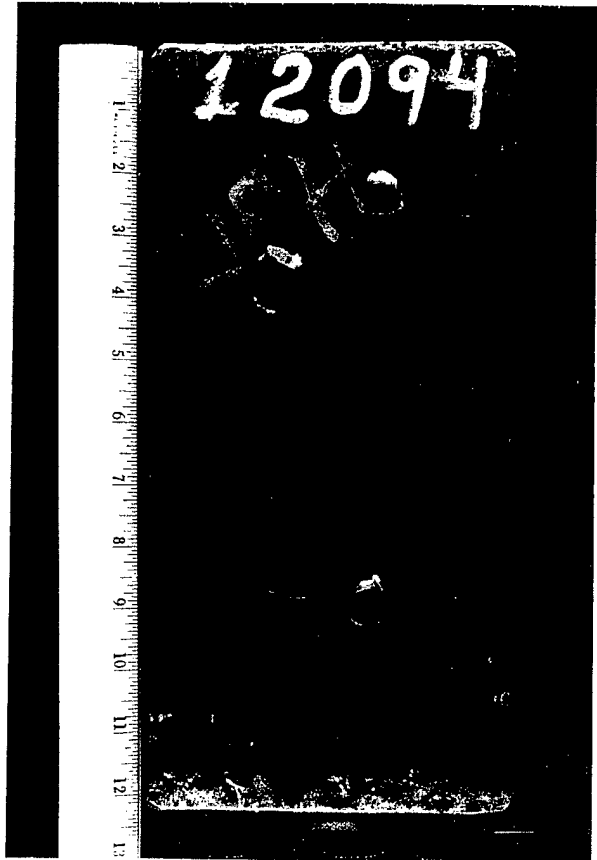








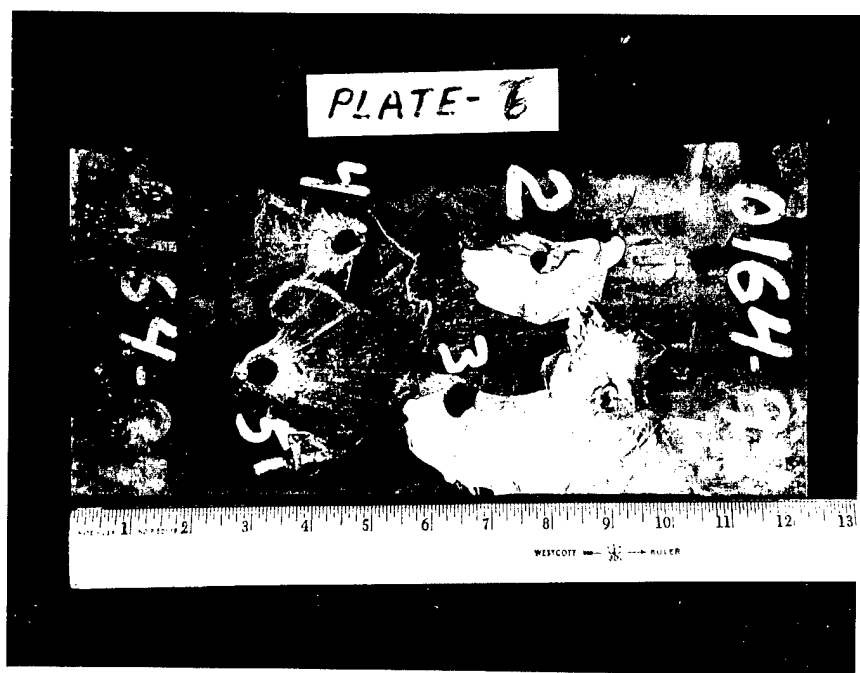


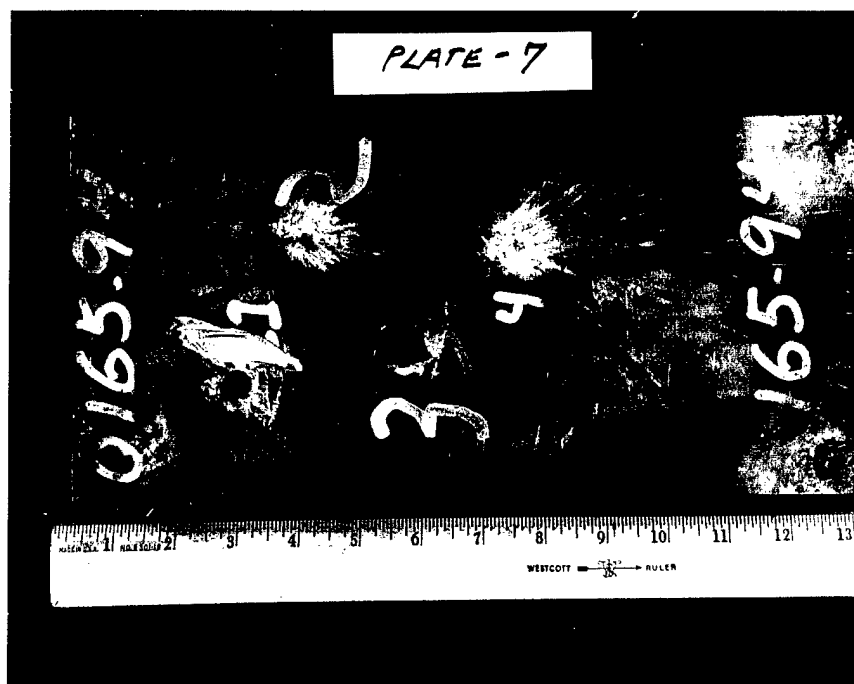


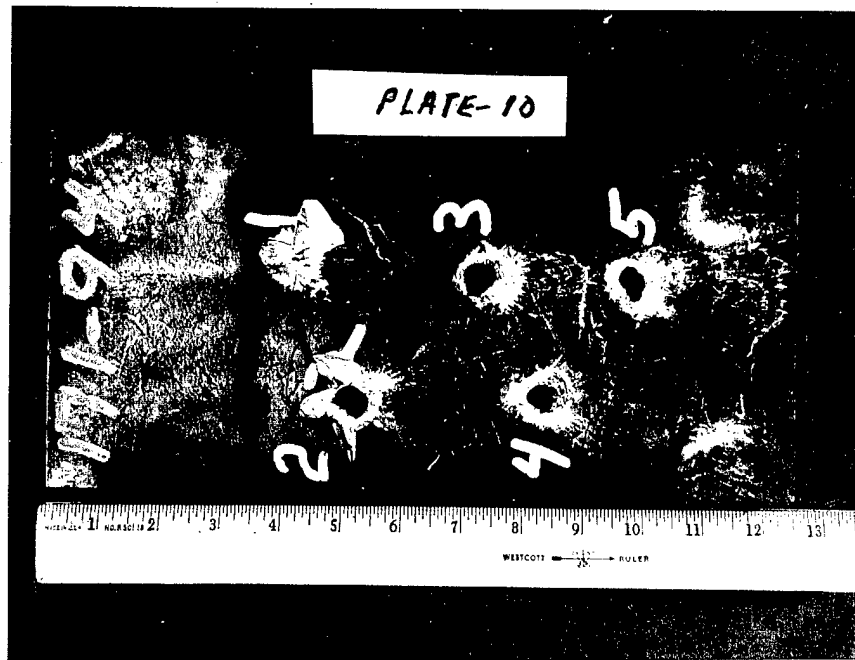
INTENTIONALLY LEFT BLANK.

APPENDIX E:
PHOTOGRAPHS OF HEAT NO. Z-62A 1ST POUR 2ND SERIES

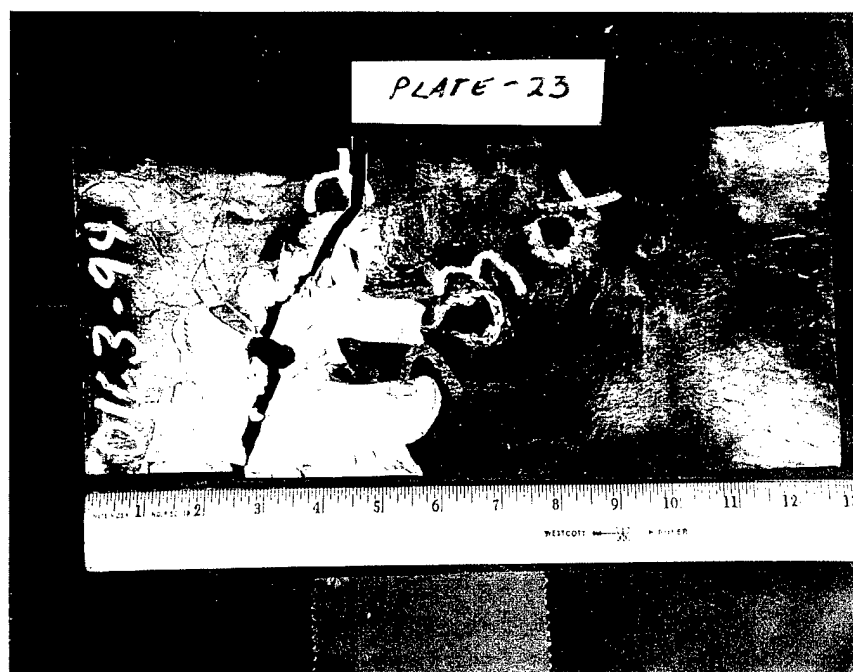
INTENTIONALLY LEFT BLANK.

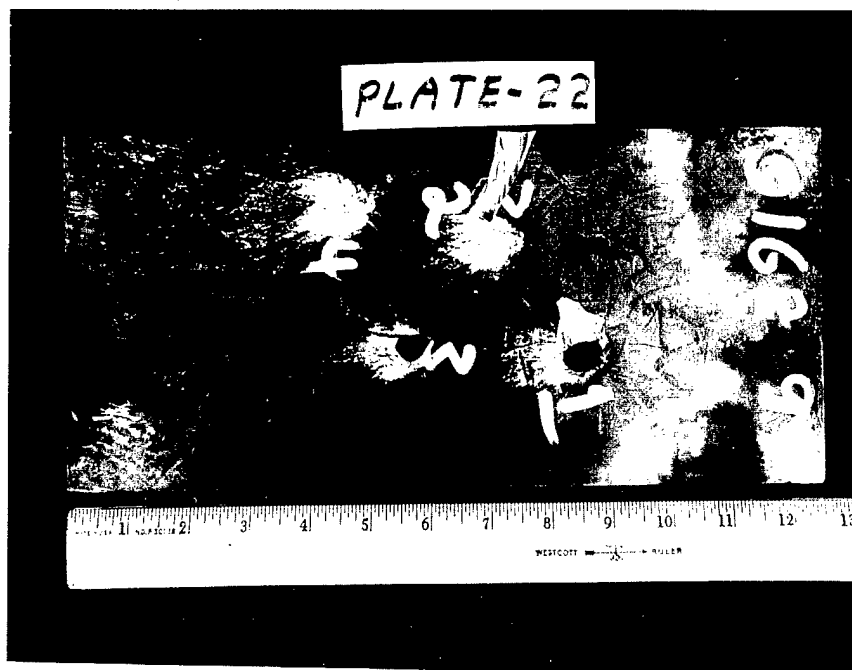


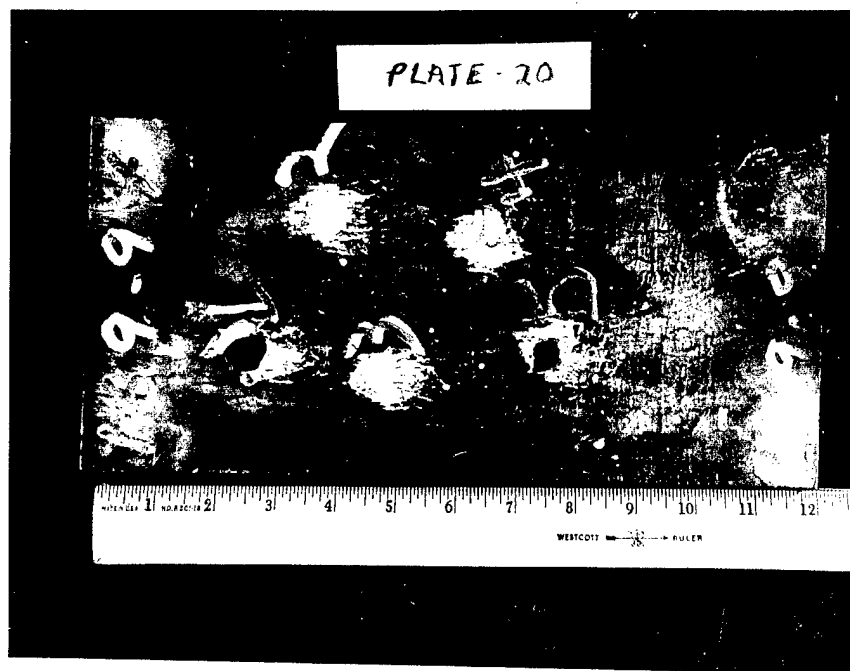


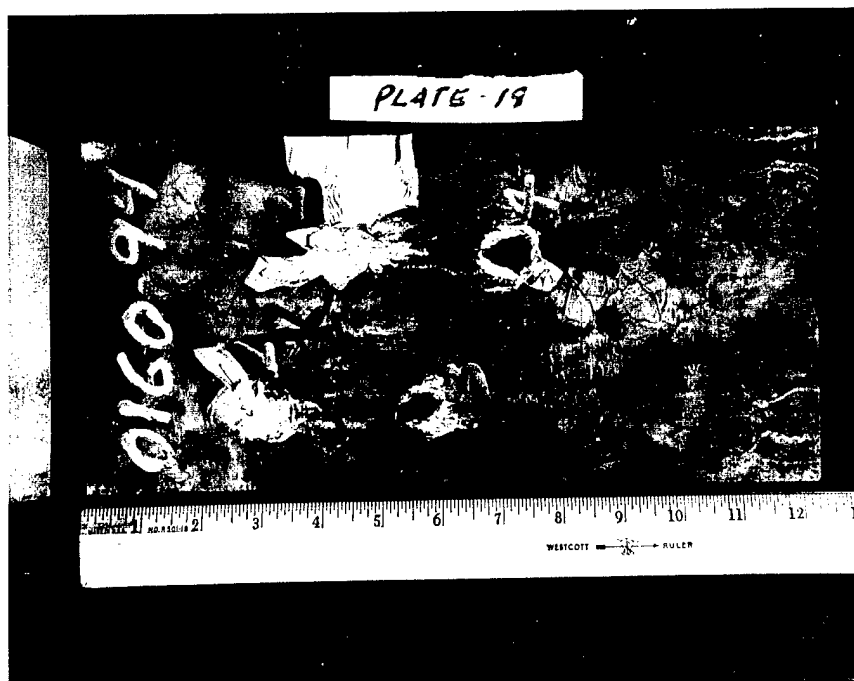












<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	DEFENSE TECHNICAL INFO CTR ATTN DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TP 2800 POWDER MILL RD ADELPHI MD 20783-1145
	<u>ABERDEEN PROVING GROUND</u>
2	DIR USARL ATTN AMSRL OP AP L (305)

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	OUSD RE THE PENTAGON WASHINGTON DC 20301
4	DIRECTOR USARL ATTN AMSRL OP SD TP TECH PUBLISHING BR AMSRL OP SD TA RECORDS MGMT AMSRL OP SD TL TECH LIB AMSRL SS 2800 POWDER MILL RD ADELPHI MD 20783-1197
2	COMMANDER DEFENSE TECH INFO CTR ATTN DTIC FDAC 5010 DUKE ST CAMERON STATION BLDG 5 ALEXANDRIA VA 23304-6145
1	COMMANDER ARMY RESEARCH OFFICE ATTN INFO PROCESSING OFC PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
1	COMMANDER US AMC ATTN AMCSCI 5001 EISENHOWER AVE ALEXANDRIA VA 22333
1	COMMANDER US ARMY MISSILE CMD ATTN AMSMI RD CS R DOC REDSTONE ARSENAL AL 35809
1	COMMANDER US ARMY ARMAMENT MUNITIONS and CHEMICAL CMD ATTN TECH LIB DOVER NJ 07801
1	COMMANDER US A NATICK RSRCH DEV AND ENGINEERING CTR ATTN SATNC MI TECH LIB NATICK MA 01760-5010

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER US ARMY SATELLITE COMM AGENCY ATTN TECH DOCUMENT CTR FORT MONMOUTH NJ 07703
2	COMMANDER US ARMY TACOM ATTN AMSTA ZSK AMSTA TSL TECH LIB WARREN MI 48397-5000
1	COMMANDER TECH INFO DIV ATTN TECH LIB DUGWAY PROVING GROUND UT 84022
4	DIRECTOR BENET WEAPONS LAB LCWSL USA AMCCOM ATTN AMSMC LCB TL AMSMC LCB R AMSMC LCB RM AMSMC LCB RP WATERVLIET NY 12189
3	COMMANDER US ARMY FOREIGN SCI AND TECH CTR ATTN AIFRTC APPLIED TECH BR G SCHLESINGER 220 7TH ST NE CHARLOTTESVILLE VA 22901-5396
1	COMMANDER US ARMY AEROMEDICAL RSRCH UNIT ATTN TECH LIB PO BOX 577 FORT RUCKER AL 36360
1	COMMANDER US ARMY AVIATION TRAINING LIB ATTN BLDG 5906-5907 FORT RUCKER AL 36360

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER USA AAS ATTN TECH LIB FORT RUCKER AL 36360
1	COMMANDER CLARKE ENG SCHOOL LIB ATTN LIBRARY 3202 NEBRASKA AVE N FORT LEONARD WOOD MO 65473-5000
1	COMMANDER US ARMY ENG WATERWAYS EXP STA ATTN RSRCH CTR LIB PO BOX 631 VICKSBURG MS 39180
1	COMMANDANT USA QUARTERMASTER SCHOOL ATTN QUARTERMASTER SCHOOL LIB FORT LEE VA 23801
1	US ARMY AVIATION R&T ACTIVITY LANGLEY RSRCH CTR ATTN MS-266 AVSCOM HAMPTON VA 23665-5225
1	NAVAL RSRCH LAB ATTN CODE 6384 WASHINGTON DC 20375
1	CHIEF OF NAVAL RSRCH ATTN CODE 471 ARLINGTON VA 22217
2	COMMANDER US AIR FORCE WRIGHT RSRCH & DEV CTR ATTN WRDC MLLP M FORNEY JR WRDC MLBC S SCHULMAN WRIGHT-PATTERSON AIR FORCE BASE OH 45433-6523

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	US DEPT OF COMMERCE NIST ATTN S M HSU CHIEF CERAMICS DIV INST FOR MATERIALS SCIENCE AND ENGINEERING GAITHERSBURG MD 20899
1	COM ON MARINE STRUCTURES MARINE BOARD NATL RSRCH COUNCIL 2101 CONSTITUTION AVE NW WASHINGTON DC 20418
1	MATERIALS SCI CORP SUITE 250 500 OFC CTR DR FORT WASHINGTON PA 19034
1	CHARLES STARK DRAPER LAB 555 TECH SQUARE CAMBRIDGE MA 02139
1	GENERAL DYNAMICS CONVAIR AEROSPACE DIV ATTN MFG ENG TECH LIB PO BOX 748 FORT WORTH TX 76101
1	NASA LANGLEY RSRCH CTR HAMPTON VA 23665-5255
1	US ARMY VEHICLE PROPULSION DIRECTORATE NASA LEWIS RSRCH CTR ATTN AMSRL VP 2100 BROOKPARK RD CLEVELAND OH 44135-3191
1	DIRECTOR DEFENSE INTELLIGENCE AGENCY ATTN ODT 5A F JAEGER WASHINGTON DC 20340-6053
1	US ARMY COMM & ELEC CMD ATTN TECH LIB FORT MONMOUTH NJ 07703

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	USA RSRCH LAB ELECTRONIC POWER SOURCES DIRECTORATE ATTN TECH LIB FORT MONMOUTH NJ 07703
1	MIA CINDAS PURDUE UNIVERSITY 2595 YEAGER RD WEST LAFAYETTE IN 47905
1	PRESIDENT AIRBORNE ELEC & SPECIAL WARFARE BOARD ATTN LIBRARY FORT BRAGG NC 28307
	<u>ABERDEEN PROVING GROUND</u>
1	DIR USAMSAA ATTN AMXSY MP H COHEN
11	DIR USARL ATTN AMSRL WT AMSRL MA PD (10 CPS)

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1193 (Squillacioti) Date of Report September 1996
2. Date Report Received _____
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

CURRENT
ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD
ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

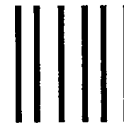
OFFICIAL BUSINESS

BUSINESS REPLY MAIL

FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR
U.S. ARMY RESEARCH LABORATORY
ATTN: AMSRL-MA-PD
ABERDEEN PROVING GROUND, MD 21005-5069



NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

